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PSYCHOLOGY

APPLIED TO EDUCATION

BY

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POITIERS

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TRANSLATOR'S PREFACE.

Monsieur Compayré himself no longer needs an introduction to the American educational public, for his books have been as extensively read and appreciated in this country as in France. With the possible exception of Page's *Theory and Practice of Teaching*, Compayré's *History of Pedagogy* has probably had more readers than any other educational work published in this country within the last ten years. This book marks an epoch in the professional literature of teaching, for it has created a taste and a place for the historical study of education which are likely to remain as a permanent endowment of the teaching profession.

Breadth of view, sobriety of judgment, critical insight, and perspicuous statement, are the sterling qualities that pervade all of M. Compayré's books. They bear evidence of wide reading, and at the same time of originality taken in its best sense,—the assimilation of material drawn from a wide field of exploration and the creation of an organic whole by the processes of independent thinking. Such books are valuable, not only for the light they throw on the art of teaching and educating, but for their wholesome stimulus to personal reading and reflection.

Mr. Bain is doubtless right in saying that the largest chapter in the science of education is psychological; but as Psychologies are usually written there is much in them which is not convertible into guidance for the teacher's use. A mere cyclopædia of mental science, written by an analyst who makes an exhaustive description and classification of mental phenomena, is practically useless for teachers who are in search of light and help in their art. For this purpose the mind must be conceived, not as an inert object to be dissected, but as a living organism manifesting the phenomena of assimilation and growth. The teacher needs

to know, in their proper function and sequence, the major movements of the mind as it is engaged in the act of learning. This, in the main, is M. Compayré's mode of interpreting psychology, and to this is due, in its mode of treatment, the peculiar excellence of this manual. In its statement of doctrine and application it is profound without being obscure, and simple without being commonplace. There are thousands of teachers who have neither the taste nor the leisure to master the details of educational science, nor even to read the profounder treatises on the science and art of teaching, but who are sincerely anxious to find a rational basis for their art; and for all such I know of no book that I can commend so heartily as Compayré's *Psychology Applied to Education*.

I have ventured to supplement the original work of M. Compayré by adding Chapter XV., in which I have attempted to present a synoptical view of the main phases of the mind's activities when engaged in learning. I hope it may serve as an aid in interpreting the preceding chapters, and as a guide to teachers in their subsequent studies. It is a mere outline, and should be accepted as such only.

In the preparation of this book for the press I have been aided at every step by Professor Wickliffe Rose, A.M., of the Peabody Normal College, and I am glad to make this public acknowledgment of his valuable assistance.

W. H. PAYNE.

NASHVILLE, TENN., January 10, 1893.

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PSYCHOLOGY

APPLIED TO EDUCATION.

A.—PHYSICAL EDUCATION.

CHAPTER I.

GENERAL HYGIENE.

General Considerations.—It is not merely for the purpose of gaining a theoretical knowledge of the laws of human nature that we have just studied the elements of psychology:[1] our aim was especially to prepare for the study of pedagogy. If it is important, indeed, to know man, it is not so much to be able to enumerate learnedly his different psychological functions, as to be able to succeed practically in elevating him, in moralizing him. Pedagogy and ethics are simply applied psychology.

To undertake the direction of education without having analyzed the faculties of human nature, would be to run the risk of committing the grossest errors; it would be to go astray, to walk at random like a traveller in an unknown country without a map before him. On the other hand, equipped with proper psychological observations, the edu-

[1] *Psychologie appliqué à L'Éducation: Notions Théoriques.*

cator is prepared to determine the theoretical and general laws which govern the development of mind and character; and, moreover, what is not less important, he is prepared easily to discern the tendencies and inclinations which are peculiar to the individual nature of each of his pupils. It is not possible to act effectively on the character of a child until we have come to know it. Now, without the key which psychology puts into our hands, the child would remain to us an insoluble enigma.

Let us, therefore, turn to account the knowledge acquired by the study of psychology. By adding to this some elementary notions of anatomy and physiology, we shall have collected all the principles with which to construct the science and art of education.

Different Divisions of Education.—From the knowledge of man, the duality of body and mind, and from the diversity of the mental faculties, it follows that education comprises several divisions, which correspond to the essential divisions of the human being. "The end of education," says Laboulaye,[1] "is to permit each individual to attain the most complete development of his body, mind, and heart." Or again, as we have expressed it, "Education is the sum of the reflective efforts by which we aid nature in the development of the physical, intellectual, and moral faculties of man."[2] In other words, there is a *physical education*, an *intellectual education*, and a *moral education*, really distinct from each other, the first tending to develop and strengthen the body; the second, to cultivate the intellectual faculties and impart positive knowledge; the third, to form the heart and the will.

[1] Laboulaye, *Les méthodes d'enseignement*, 1877.

[2] See Compayré's *Lectures on Teaching*, pp. 12, 13.

But on the other hand, psychology has taught us to recognize, in the diversity of functions, the unity of the human being, the solidarity of all the faculties. From this it evidently follows that the different divisions of education should *aid* one another, each *complementing* the others, and all harmoniously coöperating in the same work.

The higher emotions and the strength of character which moral education seeks to guarantee to us, depend, in part, on the soundness of judgment and the firmness of knowledge which are the proper end of intellectual education.

Is it not evident, on the other hand, that the intellectual faculties expand more safely under shelter of a pure heart and a sound will? And, finally, by reason of the intimate relations between the physical and the moral, it is no less evident that a robust and sound body is the necessary condition of the intellectual and moral development of man.

Importance of Physical Education.—We shall say nothing new in affirming that a vigorous crusade is now taking place in favor of physical education.[1] This movement of opinion has its explanation in several causes:

1. Owing to the progress of science, we have come to appreciate better than we formerly did the truth of the old adage: *mens sana in corpore sano*, a sound mind in a sound body. We are no longer to believe, as did the mystics of the Middle Age, that, in order to strengthen the mind, the body must be impoverished and weakened. The correlation of physical energy and mental power is an established fact.

[1] Among other facts, to say nothing of books, we mention the organization of the "Society for the Propagation of Physical Exercises," Jules Simon, president, and of the "National League of Physical Education," M. Berthelot, president.

2. The growing demands of courses of study, the intensity of the intellectual labor imposed upon the rising generation in a society where the struggle for existence is every day becoming fiercer and where the victory falls to the best instructed, and lastly the cerebral fatigue resulting from these,—all this warns the educator that it is more and more necessary to compensate and offset this larger expenditure of mental force by a judicious corrective of play, recreation, hygienic attention, and by everything that may serve to consolidate the physical forces.

3. On the other hand, in the general conditions of modern life, the inevitable deterioration of health in the crowded population of large cities, the refinements of civilization, the pernicious influences of alcoholism, in everything that tends to degrade the human species, to say nothing of a fatal decadence of a worn-out race, we find a series of new reasons for striving against physical degeneracy by a more attentive and rational culture of the bodily organs and functions.

4. Finally, we are coming every day to appreciate more and more the expediency of introducing into education a practical preparation for professional life. Manual employments justly hold a place of honor in the school. Even princes learn a trade: the Emperor of Germany, it is said, is a bookbinder. But what is only a recreation and whim for some is a necessity for others; hence there is a virtual obligation to develop through physical education the qualities of agility and skill, manual dexterity, quickness of movement; in a word, everything that makes a good workman.

End of Physical Education.—From these considerations, it follows that physical education has for its general end

the *health* and *strength* of the body, and for its incidental end, *skill*. Let us add to this, *beauty*, after the example of the ancient Greeks, who sent their children to the gymnasium, not merely to supple the members, to harden the muscles, but also to develop the plastic forms of the body.

To be in good health, to be vigorous and robust, to be skillful with the hands and the fingers, and, if we can, to be beautiful and to remedy as far as possible those infirmities which disfigure and deform,—such are the demands of physical education. Doubtless, it is nature, often, which puts us in an attitude to conform to them by the gifts which it bestows upon us, by the temperament and constitution with which it endows us at birth; but human art also affords certain means for aiding us in preserving and increasing the benefactions of nature or in correcting its defects.

Different Means of Physical Education.— The various means which physical education may employ are summed up in two words, *hygiene* and *gymnastics*.

On the one hand, there are certain precautions to be taken and certain principles to be observed, in order to maintain the bodily organs and vital functions in their integrity. This is the distinctive end of hygiene.

On the other hand, the body, as well as the mind, needs movement, exercise, activity; and this purpose is served by gymnastics, play being also included in this term.

Hygiene.—Hygiene is, as it were, the ethics of the body, a code of prohibitions and imperative precepts, either forbidding whatever is harmful, or recommending whatever is wholesome.

It may be defined as *the art of preserving the health*, but it is also the art of promoting the health. There is, in

fact, health and health. As Pécaut has observed, "Our pupils may not be ill, but this is not saying that they are well."[1] There are numbers of people in the world whose health is so precarious that they are content to escape death. But these sickly and suffering existences do not suffice for the rude labor of life. We should demand of hygiene a health that permits us to live completely, to meet all our obligations, and especially to avoid being, in the least, a burden or an occasion of perpetual anxiety to those who surround us and love us. We are culpable if, by our imprudence, we shorten our life and are taken prematurely from our family, which is dependent upon us. We are guilty also, if, through lack of care, through thoughtlessness, through voluntary or involuntary disobedience to the laws of hygiene, we sacrifice our health, and are not able to acquire the strength necessary for the performance of all our duties. "Nothing facilitates the dispatch of business," says Bacon, "so much as good health; unstable health too often forces vacations upon us."

Hygiene, according to Rousseau, is not so much a science as a virtue. In reality, it is first a science founded on the laws of life; and when practiced, it becomes a virtue, which Mr. Spencer rightly calls *physical morality*.

Our first duty is, in one sense, to live, and to live a long time. Now, it often happens that a man does not die, but kills himself. He does this because he has not followed the precepts of hygiene, that preventive medicine which, in a certain measure, enables us to dispense with all others.

Hygiene According to Horace Mann.—Horace Mann, with his usual eloquence, pled the cause of hygiene before his fellow-countrymen, and won it, since, in 1842, he succeeded

[1] *Hygiène des écoles primaires*, Paris, 1884, p. 301

in getting instruction in elementary hygiene admitted into their courses of study. He had learned to pity both those who, young or old, die prematurely, and those who prolong in a state of infirmity or illness, a languishing existence painful to themselves and useless to others. How many young lives are cut down in tender years! And how many millions through feeble health are lost to family and society! Allowance being made for nature and inevitable fatalities of constitution, is it not still true that many of those maladies and these premature deaths might have been avoided if there had not been, through ignorance or voluntary neglect, a transgression of the laws of health and life?

"Three quarters of a century ago," says Horace Mann, "the fact of the identity of electricity and lightning was known to scarcely a dozen men in the world. Now it is not only a matter of universal knowledge among the educated, but even children are familiar with it; and every individual in the country participates in the practical benefits of the discovery of Franklin. In the same way an acquaintance with the fundamental laws of health and life may be and must be popularized. The reasons are far stronger in the latter case than in the former; for where lightning has ever destroyed one victim or one dollar's worth of property, the infraction of the physical laws has destroyed its thousands of lives and its millions of wealth. . . . . The greatest happiness and the greatest usefulness can never be attained, without that soundness of physical organization which confers the power of endurance, and that uninterrupted enjoyment of health which ransoms the whole of our time and means from sickness and its expenditures. In the great work of education, our physical condition, if not the first step in point of importance, is the first in the order of time. On the broad and firm foundation of health alone can the loftiest and most enduring structures of intellect be reared; and if on these sublime heights of intellectual eminence the light of duty and benevolence,—of

love to God and love to man,—can be kindled, it will send forth a radiance to illumine and bless mankind." [1]

General Hygiene and School Hygiene.—Hygiene has precepts for all men, rules applicable to all ages and conditions; this is called *general hygiene.* But it has also special precepts for the different conditions of life; it adapts its rules to the different environments in which we are called to live. We have military hygiene, industrial hygiene, rural hygiene, etc., and especially *school hygiene.*

School hygiene treats first of the different material conditions of the school—the location, construction, lighting, heating, etc. In the second place, it addresses itself directly to the student, tracing for him a line of conduct in whatever concerns the duty of cleanliness, meals, clothing and sleep.

We shall not enter here into the details of these rules. A few general observations will suffice as a preparation for their study.[2]

Above all, let us remember that we are not simply to adopt in the interest of our children and our pupils all the measures which hygiene enjoins, but rather to accustom them to comprehend their importance and to observe them in whatever they have to do.

Physical Education according to Herbert Spencer.—Of all the modern writings on this subject, that which may best serve as an introduction to our study is certainly Herbert Spencer's essay on physical education. Mr. Spencer, like all his countrymen, attaches an extreme importance to physical education. Since the time of Locke, it has been one of the

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[1] *Sixth Annual Report of the Board of Education of Massachusetts*, p. 159–60.

[2] See *Le programme d'hygiène* for normal schools.

traditions of English pedagogy to take great care of our "house of clay."[1] England alone could have given rise to a sect professing *muscular Christianity*, which succeeded a few years ago in calling together a number of adherents, who, through pious motives, attempted to strengthen their body, just as the Christian ascetics of former times mortified and enfeebled the body through similar motives.

Mr. Spencer, opposing the negligence which is too common to parents when the physical education of their children is concerned, points out the zeal which animates these same parents when it is a question of raising animals.

A French author, Eugene Paz, had already made the same observation:[2]

> "Propose to a father, elector, candidate, or even an officer elect, to restrict the hygienic regimen of his horse or his ass to the amount of physical exercise and material attention that he finds sufficient for the health and development of his son, who is a pupil in some institution of learning, and he will revolt, declaring that it is necessary to apportion to the domestic animals fresh air and movement just as well as hay and oats."

The reflections of Mr. Spencer, often just and always pungent, bear on such questions as food, clothing, physical exercise, the effects of over-study, and excessive cerebral excitement.

As concerns diet, he maintains that the food of children should be abundant, varied, and highly nutritious. He states the principle that "the degree of energy depends essentially on the nature of the food." In direct opposition to Locke, who favors proscribing meat from the dietary of children, he affirms, from his own experience, that six

[1] *Thoughts on Education*, p. 3.

[2] E. Paz, *La gymnastique raisonnée*, *1876*, p. 2.

months' purely vegetable diet permitted him to verify the fact of a corresponding diminution in energy of both body and mind. Mr. Spencer is right in saying that "eating too much and eating too little are both bad," and in insisting on the danger of insufficient nourishment; but we do not agree with him that there is an exact and absolute ratio between the quantity or variety of nourishment and the development of mental energy. And when we think of all the families to which poverty forbids even a pretension to the luxury of an abundant and varied diet, we find some pleasure in thinking that Mr. Spencer exaggerates, and that a substantial diet, of whatever kind, satisfies the needs of the body. Mr. Spencer is wrong again, when, proclaiming the infallibility of instinct, he advises parents to satisfy without restriction the appetites of their children. In the matter of appetite, as in everything else, the natural tastes are by no means a sure guide; they often go astray, become depraved, and tend easily to exaggeration, and gluttony, for example, is not an inappropriate term.

Mr. Spencer's observations on clothing—and here we heartily agree with him—proceed on the same principle, namely: that we should rely upon sensations, should observe nature, which demands warmth of clothing, and not fashion, which sometimes delights in light and insufficient costumes.

"Our observations are, then, that while the clothing of children should never be in such excess as to create oppressive warmth, it should always be sufficient to prevent any feeling of warm or cold; that instead of the flimsy cotton, linen or mixed fabrics commonly used, it should be made of some good non-conductor, such as coarse woollen cloth; that it should be so strong as to receive little damage from the hard wear and tear which childish sports will give it; and that its colors should be such as will not soon suffer from use and exposure."[1]

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[1] Spencer's *Education*, p. 251.

Cleanliness.—Cleanliness and care of the skin are no less necessary to health than sufficiently warm clothing, or wholesome, substantial food. Water is to the skin, say hygienists, what air is to the lungs. Hence, in certain religions, the sacred and obligatory character of the ablutions.

Daily attention to cleanliness and frequent baths, hot or cold, according to the season; these are the requirements demanded by our appearance and our dignity, not less than by the consideration of health. Imperative as are these obligations for all people, they are still more so for children crowded together in the same schoolroom, and, consequently, more exposed to contagious diseases.

The duty of looking after the cleanliness of children, doubtless, belongs chiefly to the family; but the teacher may exercise a useful supervision by the daily inspection which the law requires him to make, and also by the recommendations which it is his duty to address to families.

"To the objections which poor parents may make to him, the teacher will reply that one does not need to be rich in order to be clean; that, moreover, cleanliness being the only luxury which is allowed the poor, parents should give their children at least this luxury; and as it requires but little money to clothe a child properly, so it requires but little time to see to it that he takes care of his clothes and his person.

"I will add that man is most often physically as well as morally what his education has made him, and that if children contract early habits of cleanliness, it is a guaranty of health, that is, of strength for the work which they have to do in youth."[1]

Temperance.—Hygiene does not content itself with rec-

[1] See *Hygiène des écoles primaires*, p. 206; *Projet d'instruction*, by M. Jacoulet.

ommending a certain number of formal practices; it appeals also to the moral powers of man, to determine him to live temperately, to use moderation in all things.

The general principle of all hygienic prescriptions is that we should constantly apply the old adage: "avoid excess." The beginning of wisdom, in physical as well as in moral education, is to *use without abusing*, to avoid excesses, to seek the golden mean, and to adapt one's activities to his powers and his circumstances. The evil is not in drinking when we are thirsty, nor in eating when we are hungry: it is in drinking and eating more than we need. The evil is not in the inveterate use of tobacco, but in using it to excess. Intemperance under all its forms is fatal to health, as much so in cases of intellectual exercise as in the immoderate gratification of bodily appetites. And it suffices that we give loose reins to a single one of our passions in order that through this one fissure infirmities and diseases penetrate the organism, thus rendering useless the efforts which we have made in all other directions to conform to hygienic laws.

Privations.—To be temperate is not simply to use things with discretion and moderation; it is to be able to do without them when necessary. Our physical education is incomplete if it has not accustomed us from childhood to accept, when circumstances demand it, a momentary renouncement of the comforts and ordinary conveniences of life. A soldier who has not accustomed his stomach to bear a few hours of hunger makes a sorry figure on the march. On the other hand, while we do not wish to revive ancient asceticism in our manners, let us guard against falling into the opposite extreme and sacrificing too much to our physical wants. In a body too highly nourished, immorality

indulges in wild excesses and sudden revolts. Evil and brutal passions lodge there as though at home; and while we no longer wish bodies impaired by maceration and prolonged fasting, we also distrust temperaments heated and overexcited by excessive diet, rich food, and the daily gratification of the bodily appetites. It is not simply effeminacy or lack of vigor that is to be feared in such cases; it is worse than that—it is the violent reappearance of beastly instincts.

There is one chapter lacking in the writings of modern hygienists, namely: that on privations. In former times they were abused; yet it would be wise not to renounce them altogether. Even Comte recognized that there was good in those religious precepts which recommended men to submit voluntarily to systematic privations.[1]

"The hygienic practices," says he, "imposed by Catholicism, besides their indirect value in maintaining wholesome habits of moral submission and voluntary restraint, were the happy auxiliaries of education in general."

The Laws of Health and of Life.—We are very far from having reviewed all the subdivisions of hygiene. It will teach us further how to regulate our sleep, and to divide our time between labor and repose. It is from hygiene, also, that we learn what conditions of air and light are most favorable to health. In a word, there is not a single function of organic life for which the science of hygiene has not some useful and valuable precept.

But what is even more important than having studied these rules, is to acquire the conviction that there are in the world of life, as well as in external nature, fixed and invariable laws which *may* be known, and which *must* be

[1] Comte, *Cours de philosophie positive*, t. v. p. 307.

observed; laws which, if we are so unfortunate as to break them, avenge themselves by disease and death. Let us free ourselves from that mistaken idea by which life is still represented as a theater of chance, and which admits that the body may with impunity be given up to every fancy and caprice. Once impressed with the truth that life has its laws, just as gravitation or electricity has, it will be easy for us, by the aid of professional books and our own experience, to determine in detail the special rules which, when combined, constitute a good hygienic guide.

SUMMARY.

1. The science and the art of education suppose the knowledge of human nature. Pedagogy is only applied psychology.

2. There are three divisions in education: physical education, intellectual education, and moral education. These are founded on the three essential divisions in the human being: the organs and the functions of the body, the intellectual faculties, the emotions and the will.

3. The importance of physical education results from the close relations which unite the mind and the body. At the present day its importance has increased for several reasons: 1, the more intense intellectual effort required by continually enlarging the courses of study; 2, the various causes which go to weaken the native vigor of the constitution; 3, the necessity of preparing in school for the attainment of professional skill.

4. Physical education has a threefold end: health, strength, and skill.

5. The means at the disposal of physical education may be summed up in two words: hygiene and gymnastics.

6. Hygiene is the art of preserving and promoting health.

The prescriptions of hygiene constitute a kind of preventive medicine, which shields us from a great number of diseases and gives us the means of prolonging life.

7. Without health, neither can the individual aspire to happiness, nor the citizen completely fulfil his social duties.

8. General hygiene establishes the rules which are applicable to all conditions of life; school hygiene treats of the physical conditions of the school and the regimen of the pupil.

9. As Mr. Spencer demands, food ought to be, as far as possible, abundant and varied; clothing should be warm.

10. Cleanliness of body and clothing is an element of health as well as a duty of personal dignity.

11. The fundamental principle of hygiene is, in everything be temperate and avoid excesses.

12. Temperance does not consist simply in using things in moderation; it teaches us to do without them when necessary.

13. That which should govern our study of hygiene is the conviction that it is truly a science, establishing the laws of health and life, laws which cannot be infringed with impunity.

CHAPTER II.

THE PLAYS AND EXERCISES OF CHILDREN.—GYMNASTICS.

Hygiene and Physical Exercise.—There is a hygiene of preservation, which seeks the means of protecting the organs of life, of assuring the regular progress of the functions of nutrition, respiration, etc. But there is also a hygiene of action, so to speak, which seeks more particularly to strengthen the body, to develop and supple its members by exercising them. Exercise, or rather physical exercise, in all its forms, is the essential condition of this positive hygiene, which is the true organizer of the body, or at least nature's necessary co-laborer in the work of organizing our bodily forces.

Necessity of Bodily Exercise.—Just as our moral faculties are developed by exercises in reading, meditation or composition, so our physical faculties are developed, either by the systematic exercise of gymnastics, or by the less constrained exercise of playing and walking.

Physiologists state that the demand for exercise is no less imperative than the demand for food, and they are with good reason astonished that this particular need of the body has not received a special designation, to which it has as good a right as *hunger* or *thirst.* [1]

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[1] Dr. F. Lagrange. *Physiologie des exercises du corps.*—Paris: Alcan, 1888.

Let us analyze the results of physical exercise, and we shall be convinced that physical activity contributes in more than one way to the health of the body and of the mind.

The first advantage to be gained from physical exercise is, that while the muscles are being exercised the brain and nerves are left at rest; the mind is allowed to regain its forces; the equilibrium between physical and intellectual development is restored. The best remedy for what is called over-work is to multiply the pupil's plays and recreations.

But physical exercise has also a direct and immediate effect both on the body and on the mind itself.

As for the body, it is evident at once that exercise strengthens the muscles. The muscles, under the influence of a well-directed daily exercise, become, not only larger and firmer, but also more contractile, and consequently more capable of responding vigorously to the excitations of the will.[1] Since the muscles are the immediate agents of movement, and play a part in every kind of physical activity, the youth soon acquires thereby greater strength and agility. But, on the other hand, exercise influences the whole organism. It stimulates the functions of circulation; it sharpens the appetite and accelerates the processes of nutrition; it removes those obstructions, such as *fat*, which embarrass and encumber the working of the human machine. In a word, it gives increased activity to the organic life in all its functions, and thereby develops the organs themselves, according to a well-known law which says that "the function makes the organ." In this way, again, exercise is a source of health and strength.

For the mind, also, physical exercises are helpful, not

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[1] *Ibid.*, p. 181.

only because they leave the mental faculties time to recuperate in repose, as we have already observed, but also because, by reason of the relations no less certain than mysterious which connect thought with the brain, and the brain with the entire organism, it renews and nourishes the deep and obscure sources of the intellectual life. One needs simply to observe himself after a walk or a social game, to see that it is not the body alone which has profited by the physical exercise, but thought has become clearer, feeling more ardent, and imagination more vivid. Observe children after playing; ardor in sport is followed by ardor in study. Under one condition, however, that the exercise has not surpassed proper limit. Sports too violent or too prolonged would waste the mental forces and prevent the mind from recuperating; but moderate exercise gives it animation and life.

Physical Courage.—It is not only the health of the intelligence but still more the energy of the will that is maintained and increased by the habitual practice of physical exercise. It is known, moreover, that courage is affected by bodily vigor. With a feeble body, how hope to be a hero, or even to appear brave in the presence of danger? Intrepidity, on the contrary, and a courageous bearing in the midst of danger, are things easy enough when the will has at command a body of iron and muscles of steel. But this is not all. Physical exercise and muscular activity do more than secure to the will its instruments or tools; they develop and perfect the will itself. The child or the man who accustoms himself daily to experience bodily fatigue, and who with ardor sustains an energetic muscular effort, becomes more capable of willing; he acquires, not only more muscle, but also more mental energy. This is

why General Thomassin could say to Jules Simon, on coming from the exercises of the gymnasium or play-ground: "It is moral strength that we are going to develop."

Choice of Exercises.—There are a thousand ways of exercising one's self. Muscular labor is the same for the farmer who tills his land, as for the gentleman who fences. If the first wears out while the other grows strong, it is because the man of the world sleeps well and eats bountifully, while the peasant eats insufficiently and rests but little. This result is especially due to the fact that the fencing is only an hour's recreation for the first, while for the second his work is prolonged throughout the day.

The first rule to follow, therefore, in the choice of exercises, is to give preference to moderate exercises which do not require an excessive expenditure of muscular force; and also when indulging in violent exercises, in themselves very fatiguing, to know when to stop, and not to prolong nor repeat them beyond measure.

Another important rule is to choose exercises which benefit all parts of the body at the same time. Just as the best foods are those which physiologists call *complete foods*, that is to say, those which contain all the substances necessary to nutrition, so the best exercises are those which call into activity the greatest number of muscles at one time. Specialization is detrimental in the education of the body as well as in that of the mind. Who exercise more than dancers? But as scarcely more than their limbs are called into play, the benefit realized to the physical constitution as a whole from this muscular activity is by no means proportioned to their exertion.

Again, we are told by physiologists that the most health-

ful physical exercises are those which demand the least intellectual efforts. For a given amount of muscular labor, they say, the sensation of fatigue is the more intense in proportion as the exercise requires the more active intervention of the mental faculties; hence, preference should be given to exercises which do not demand sustained attention, which are performed mechanically or automatically, as walking, for example.

Let us observe, however, that there may be at times some interest in combining intellectual activity with muscular exercise, as happens in recreations and games, in which free play is given to the child's imaginative and inventive genius. But so far as strengthening the organs is concerned, these mixed exercises, so to speak, could not pretend to the same efficacy as the purely physical exercises, freed from all intellectual tension.

Gymnastics.—Gymnastics, strictly speaking, is a rational choice of exercises, a regular and systematic culture of the body. It is to physical activity what a good course of study is to intellectual activity. It may be defined as *the art of exercising the physical faculties.*

As has very justly been said: "The ordinary disordered and unsystematic plays, with their inconveniences, cannot replace gymnastics; and, conversely, gymnastics, regular and systematic, as it is, should by no means exclude the plays in which children abandon themselves to all the frolics of their age."[1]

In the choice and successive organization of its exercises, gymnastics is inspired by the rules which we have marked out, and by some others.

[1] M. Barthélemy Saint-Hilaire. Preface to *Gymnastique Pratique de Laisné.* p. 9.

It varies the exercises which it imposes, so that all the members may be called into action. It causes movements of the limbs to be followed by arm movements; it recommends in turn standing, swinging, and bar exercises. It employs ropes, machines, and every skillful combination of apparatus, so as to give occasion for the exercise of every muscle.

On the other hand, when it is wisely administered, it does not abuse these machines, nor the too complicated and difficult exercises of the art. It gives a marked preponderance to standing movements, to walking and running, to those simpler exercises which are more in conformity with nature, and which are none the less beneficial.

Finally, it does not forget that it is a means and not an end. It is not proposed to train professional athletes, or gymnastic experts in feats of strength; the aim is simply to make gymnastics serve the general education of the body, just as the study of the sciences is adapted to the general education of the mind. Gymnastics looks to the same end as hygiene: it aspires to perfect the organism from the triple point of view of health, strength and skill.

History of Gymnastics.—It has by no means been left for our century to discover that children need activity and exercise. Nowhere has gymnastics been honored more than among the Greeks. At Athens the gymnasium was frequented no less than the school. Not only the victors in the contests in poetry and eloquence were crowned on the Agora; but almost divine honors were there paid those who had excelled in running, boxing, and wrestling. At Rome, in the early period, men, both young and old, came every day to exercise on the Field of Mars; and up to the

last, the custom of gladiatorial combats shows that the Romans never lost their taste for physical exercises.

In the Middle Age, notwithstanding the mystic tendencies of a misconceived piety, chivalry, with its tilts and tournaments, is an evidence that gymnastics had not lost all its claims, at least among the privileged of the higher class.

In the seventeenth century, Fénelon declares that the most essential thing in the first years of life is to take care of the child's health; and the Abbé Fleury, a friend of Fénelon's, writes as follows:

"It is conducive to good health to be clean and neat, to breathe pure air, drink good water, and eat simple food; and although nature teaches us all these things clearly enough, it is well to admonish children concerning them, and to have them make of these considerations objects of frequent thought; for they easily become matters of habit. Whatever gives strength is very conducive, also, to health, which strength necessarily presupposes. Now, strength is not gained, as the masses think, by eating heartily, and drinking much wine, but by working and exercising, and by taking nourishment and rest in due measure. The exercises best adapted to everybody are: prolonged walking and standing, carrying burdens, drawing with pulleys, running, vaulting, swimming, riding on horseback, fencing, tennis-playing, and so on, according to age, and to the condition or profession for which each one is destined. I leave the details to those who may some day consent to give us a treatise on exercises: I simply make this observation, that it is very important to give children at an early age a great love for exercise." [1]

This *treatise on exercises*, which the pedagogy of the seventeenth century was already demanding, has been written by our contemporaries; and gymnastics is henceforth an established art, with its rational principles, its exact and

[1] Claude Fleury, *Traité du choix et de la méthode des études*, chap. xx.

well-defined rules—an art that may be taught, and which, since 1880, has been required to be taught in our schools. It is evident, moreover, and we shall not insist upon it, that gymnastics should vary its exercises according as it is for boys or girls, as it is taught in city schools or in country schools. But its utility is universal, and the circular of March 9, 1869, already quoted, observes, with reason, that the awkward and clumsy attitude of a great number of the soldiers from rural districts is sufficient to show how great is the necessity of suppling their limbs, or rendering their walk freer, and of teaching them to use their natural forces to better advantage.

Gymnastics for Girls.—As observed by an author already quoted,[1] "Women have need of gymnastics even more than men; for, in their case, the obstacles which civilized life opposes to physical development are far more numerous, and even much more harmful." Doubtless men have special duties, which, at first thought, seem to render gymnastic exercises more necessary for them, since, for example, these exercises prepare them for the fatigues of military life. All men are to be soldiers. Yes; but girls are to be mothers! Mr. Spencer also, in the essay which we have already analyzed, eloquently insists on the equality of the two sexes as to their need of gymnastics. Moreover, the ideal woman is not a frail, delicate creature, with a dainty appetite, incapable of all physical effort. Mr. Spencer desires for her, on the contrary, a robust development and blooming health, "however plebeian these qualities may appear."

The Pedants of Gymnastics.—However thoroughly we may appreciate the merits of gymnastics in the education

[1] Barthélemy Saint-Hilaire, Preface just quoted, p. xiii.

of girls, as well as in that of boys, we shall guard against falling into the exaggerations and whims of those whom a contemporary author aptly calls the "pedants of gymnastics," and who see the salvation of the body only in the continual practice of intricate and complicated exercises.

"There is at present a tendency to consider the trapeze as the regenerator of the human race. It seems that the art of moving our members may be acquired only after long research and profound meditations. We fall under the ferule of the pedants of gymnastics; and doubtless the time will come when we shall be as much astonished at taking exercise while walking, as M. Jourdain was at speaking prose while talking. In the universities, and even in female seminaries, may be seen the most complicated machines, and the teaching of the most difficult, and, we might say, the most grotesque, movements. Through lack of attentive discrimination, people fail to understand that many of the amusements to which children abandon themselves, are really violent exercises, while many of the exercises of formal gymnastics are simply difficult tricks." [1]

School Amusements.—These are highly recommended by Mr. Spencer, who places the free and joyous effort of activity in play far above the artificial and somewhat monotonous exercise of the gymnasium, for the special reason that the regular and systematic exercise of the gymnasium is

[1] Dr. F. Lagrange, *Physiologie des exercises du corps*, Paris, 1888, p. 209. The commission organized by the decree of Oct. 18, 1887, to revise the programme relative to teaching gymnastics, has just published its work. In President Marey's report we read the following: "The defects of the present curriculum are striking, considering the fact that it is intended ordinarily for children of both sexes; it does not take sufficient account either of the age of the pupils or of the different conditions of country and city life; it too often makes a dry routine of instruction which might be made attractive; it is based on an empirical tradition rather than on the laws of physiology and hygiene."

not accompanied with pleasure, and is the less wholesome on this account. It is not altogether correct to say that gymnastics is not accompanied with pleasure; but it is certainly less so than play, and too often, when misused, it becomes, as has been said, simply an extra task.

Then, if we would have the rising generations to grow strong, physically and morally, let us wish for them active recreations in the open air free, but at the same time supervised and regulated.

Art, indeed, should intervene to teach the child to play, to furnish him with instruments,[1] and to prepare for him either spacious courts within the enclosure of the school, or play-ground out of doors, or as they have been called, "*des prairies de jeux*."

Here is an exact statement of what is done in Switzerland, according to an eye-witness, M. Steeg:

> "The plays are all very gay, and at the same time very orderly. Girls and boys play together; a college professor organizes the games and has the general direction of them. Here is a game of ball, there a game of "graces," where twenty little girls are throwing rings all at once; here a game of lawn-tennis; there a shooting-match with cross-bows, a very popular sport in the land of William Tell. There is running, jumping, and laughing. All this is done very seriously, and yet very joyously. Every day the different schools take their turn in coming to exercise in this way in the open air and in public."[2]

[1] In a circular addressed by the rector of the Academy of Toulouse to the inspectors under his jurisdiction, we read the following: "Organized plays should count as lessons in gymnastics; children should be taught to make their ordinary recreations more active, and, hence, more hygienic. They should not be left free to amuse themselves during their recreations; hence they should be taught certain plays, base-ball, tennis, croquet, battledore, bowls, stilts, vaulting."

[2] *Revue pédagogique*, 1888, p. 217. So certain municipalities in Bel-

But it is not to be imagined that an organization of this kind is necessary to satisfy the child's need for exercise. In such matters, that which is the simplest is the best. If we have not at hand artificial machines and ready-made playthings, let us invent some. On this point we may resort either to the imagination of children or to the devotion of ingenious teachers. When we have not, as in Switzerland, a spacious play-ground, we may always find, in the vicinity of the school, a highway where it will be easy in a thousand ways to call into play the physical activity of the children.

School Promenades.—It is in boarding schools especially that it is necessary to find in walking exercises a corrective for the long hours of confinement to which the pupils are subjected. But even for the day scholars of primary schools, the walk, organized from time to time under the conduct of the teacher, may also have its utility.

The experiment has been tried, and not without success. In the circular addressed by the inspector of the Académie de la Loire-Inférieure to the instructors of his department, at the opening of the scholastic year 1887–88, we read the following:

"I desire that, at least once a month, all the scholars engage either in a pedagogical promenade with a definite purpose, (a geographical study, a visit to an historical monument or museum, studies in natural history or agriculture, a visit to a factory, etc.,) or a school walk, serving to strengthen and harden the children."

And the author of the circular, relying upon the numerous reports of teachers, testifies to the happy results of his experiment.

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gium and Germany, for lack of school grounds, have appropriated for their plays public parks and vacant lots.

Of course this exercise should not be imposed, should not be made obligatory and official. In the country particularly, where the children, in order to reach the school, have several miles to travel, the school walk would not always have its justification. But in city schools, leaving the teacher free to choose the season, the day, and the hour, it could not be too strongly recommended.

Vacation Colonies. — The purpose of physical education is not simply to preserve health that is naturally sound; it owes its attentions also to feeble constitutions; its duty is to remedy, as far as possible, the debility of frail and sickly children.

In this respect, one of the most ingenious institutions, and one of the most worthy of commendation, that has appeared in modern times, is "vacation colonies," whose origin is due to Switzerland, to a minister of Zurich, M. Bion.

Vacation colonies consist in sending for a few weeks far from the vitiated atmosphere of cities into the midst of the mountains or forests, or sometimes to the sea-shore, a certain number of poor school children, chosen from among the weakest and most anæmic. These institutions do for them what parents in rich families do for their children. Under the supervision and direction of a teacher, they go to fill their lungs with the invigorating air of the country. Vacation colonies, to be sure, do not work miracles; they do not undertake to remake impoverished constitutions in a few days. They contribute, nevertheless, to a marked improvement in the health of the little colonists; and "when they return to school," says M. Cottinet, "after having been well cared for, well nourished, well bathed, and well entertained, with glowing color, full chest, and the mind stored

with pure images and healthful ideas, these disinherited come to be envied by others."

Excessive Brain Labor.— But all gymnastic exercises would be to no purpose, all the ingenious inventions inspired by the solicitude of families or of society for the health of children would remain fruitless, if a badly conducted intellectual education, leading to exhaustion and to excess of mental labor, were to counteract the happy effects of gymnastics and bodily activity. It is not so much through lack of exercise as by the abuse of study that, in most cases, the health of children and of young people is impaired. In other terms, it is not sufficient that a few hours each day be reserved for rest, recreation, exercise, and play; it is necessary, in addition, that the studies be well regulated, proportioned to the limited powers of the child, and adapted to his age. A forced intellectual development, as Mr. Spencer observes in the last part of his Essay on Physical Education, produces either physical weakness, stunted growth, or premature death. And this is how intellectual education, of which we have now to speak, may, and should, if wisely directed, coöperate with physical education, and contribute its part to the regular development of the vital forces and to the preservation of health.

SUMMARY.

14. Hygiene does not simply permit measures of precaution and preservation: there is a positive hygiene, which makes exercise a law.

15. Physical exercises are necessary, first, because they permit the brain and the nerves to rest; second, because they directly strengthen the muscles, the immediate agents of movement and the instruments of all physical labor; be-

cause they quicken the whole organic life; and finally, because they affect even the mind, by reason of the relations which exist between the intellectual and the physical life.

16. Physical exercises develop the will, because the will intervenes in the effort of all prolonged muscular activity.

17. Among physical exercises, the best are those which do not require an excessive expenditure of muscular force, those which benefit all parts of the body, and which may therefore be called complete exercises; and lastly, those which require the least intervention of the cerebral faculties.

18. Gymnastics may be defined as the art of exercising the body. In the selection of the regular and systematic exercises which it organizes, it is inspired by the preceding rules. Its purpose is not to make gymnasts or professional athletes, but to provide for the general education of the body.

19. Gymnastics was held in honor among the Greeks and Romans; even in the Middle Age, during the time of chivalry, it was not without its champions. As early as the seventeenth century, pedagogy demanded that a "treatise on exercises" be written. This treatise has been written under various forms in our own time; and gymnastics is henceforth an established art, which may be and should be taught.

20. Gymnastics is no less necessary for girls than for boys: boys are to be soldiers, but girls are to be mothers.

21. We should not, however, make an abuse of systematic exercises and complicated difficulties, and should not trust ourselves exclusively to those who have been called the pedants of gymnastics.

22. To the systematic exercises of gymnastics should

be added school amusements and those active recreations in which, with greater liberty, the child abandons himself to all his frolics.

23. We can but recommend the use of school promenades, organized either for purposes of instruction or for accustoming the children to walk.

24. The institution of vacation colonies should be made general, in order to counteract the loss of vitality and general debility of the poor children who live the whole year in a vitiated atmosphere.

25. Unless, by a wise regulation of studies, all excessive brain work, all abuse of intellectual application, be avoided, the most careful physical education would amount to nothing.

B.—INTELLECTUAL EDUCATION.

CHAPTER III.

DEVELOPMENT OF THE FACULTIES AT DIFFERENT AGES. THEIR APPLICATION TO THE DIFFERENT BRANCHES OF KNOWLEDGE.

Intellectual Education.—Intellectual education has a two-fold purpose: to store the mind with the greatest possible amount of knowledge or truth; and, at the same time, to form the mind itself, to develop the faculties of the intelligence.

The range of the knowledge to be communicated is more or less extended, according as the instruction is of the primary, secondary, or higher grade. Things are taught in the college that are not taught in the school, and in the university what is not taught in the college. But the higher aim everywhere, in the humblest village school as well as in the highest course of the Sorbonne, is to form minds, to develop sound and robust intelligences in possession of their essential organs, not simply furnished with a certain amount of knowledge, but capable of growth and of exercising their powers in acquiring new knowledge; and capable especially of manifesting themselves in sound judgment and right reason.

If such is the ideal purpose of instruction in all grades, it may be said that it is in primary instruction we find it

most necessary to propose this end, and, at the same time, most difficult to attain it.

Difficulty and Necessity of Intellectual Education.—In the school, in fact, we have less time at our disposal than in the college. We have leisure to store the child's mind with but a small amount of elementary knowledge. We simply skim over the sciences, which, when studied thoroughly, by the very nature of their related ideas and logically connected reasonings, carry with them order, method, exactness, and reason. On the other hand, we can not think of making a thorough study of history, that school for the judgment, nor of advancing very far in the study of literature, in which we acquire delicacy and refinement of thought. In short, in a course of instruction which is necessarily limited and of short duration, we do not find for organizing the child's intelligence the resources which are offered in a full course of studies pursued for a series of years.

The difficulty, therefore, is great; so great that the old idea that there is, properly speaking, no intellectual education in the primary school, still prevails.

"It is an absolute necessity," says the author of a recent book, "that primary instruction be very elementary, and, condemned to be very elementary, it is an absolute impossibility that it have any educative value whatever."[1]

If these affirmations were as true as they are positive, it would be equivalent to closing the schools. But the summary judgment of M. Goumy is not sufficient to settle the question; and an appeal may be taken from it. However elementary primary instruction may be, it is evident that,

[1] Édouard Goumy, *La France du centenaire*, 1889, p. 274.

by a wise selection of studies, by a skillful direction of the instruction, and by the use of active and living methods, which, applied even to very elementary knowledge, appeal to the minds they are training, it is evident, we repeat, that, in this way, the primary school, in spite of its detractors, may have an educative value. Although the primary teacher has less means at his command than the teacher in the secondary school, we maintain that it is, nevertheless, his imperative duty to form clear-sighted, well-disciplined, and vigorous minds. That he can only half-way defend his pupils against the darkness of ignorance, that he is denied the ambition of giving them that intellectual equipment which always enables the highly cultured mind the more easily to attain its freedom, is the very reason why he should, by redoubled effort, and a more consummate art, seek to arm the intelligence of the common child against prejudice and the weakness of an untrained judgment.

Education and Instruction. — The principal means employed in intellectual education is instruction. There is, in fact, no other way to develop the faculties than by exercising them. Now, intellectual exercise is study, and teaching is causing a pupil to study.

To know well what he teaches is evidently the first qualification of the teacher. But this is not sufficient: he needs furthermore to know how to use what he knows so skillfully as to make of it an instrument of intellectual culture. To this end, he needs at least two things, over and above his natural qualifications: (1) to have studied the nature of the child until he understands the progressive development of the faculties, at different ages, sufficiently to adapt his instruction to the capacity of the minds of his pupils; (2) to have reflected on the nature of the different orders of

knowledge, and the methods adapted to the study of each science, so as to make appeal to this or that faculty as the case may require.

In other terms, the teacher should know, as philosophers say, both the *subject* and the *object* of the instruction. By the subject, we mean the child who studies, and to the natural growth of whose mind the order and progress of studies must be adapted. By object, we mean the different branches of knowledge which compose the curriculum of studies, and which, to be learned, demand the application, at one time, of the faculties of memory and imagination; at others, those of judgment and reason.

It is by not having conformed to one or the other of these two conditions, that inexperienced teachers sometimes fail in the intellectual education of their pupils. They overwork and abuse the intelligence of the child, by imposing upon it efforts out of proportion to its strength, by burdening it too soon with abstractions and general formulas, or they unskillfully employ faculties which are not adapted to the work to which they apply them, as, for example, in calling memory alone into service in the study of arithmetic, or, inversely, pure reason, in the study of physics.

Psychology of the Child.—In a word, what we teach is of less importance than our manner of teaching; so that the meager amount of knowledge imparted may be compensated for, in part, by the methods employed in imparting it.

Let us not imagine that the sciences, or that knowledge of any kind whatever, may pass from the book which contains it to the mind which is to assimilate it, without preparation or precaution, without the teacher's seeking to know under what form the instruction should be given, by what

favorable avenue the intelligence of the child is open to his lessons, and what approaches, on the other hand, are still closed in a mind that develops slowly day by day.

Hence the importance of the reflections on infant psychology, to which we invite the attention of all teachers.

A point of prime importance, which can not be contested, is that the mental faculties are subject to the law of development, or progressive evolution. Nothing in nature is made at once, by a single stroke, by a sort of improvised miracle. The mind, like organized bodies, as plants, for example, is formed little by little, by insensible degrees. Hence this pedagogical conclusion: in the development of the intelligence, all times are not equally favorable for beginning this or that study. It is necessary that the teacher's art introduce into the course of instruction an evolution or progression analogous to that which nature herself realizes in the intellectual faculties.

Innate Faculty. — Another essential truth is, that the mind is not merely the result of successive acquisitions of experience, and is not made up merely of the knowledge which we store away from day to day.[1] It does not start from nothing to achieve everything. It possesses at birth innate tendencies and aptitudes. It is not, as certain educators, notably Comenius and Diesterweg, seem to think, an empty capacity, or *tabula rasa.*

"Even before birth, there are inscribed on this tablet, in many obscure characters, traces of inscriptions made by the repeated impressions for innumerable generations. So effaced and indistinct are these inscriptions, that the tablet has been regarded as clean. But the more we observe the child, the better we succeed in easily deciphering the once illegible inscriptions which he

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[1] See Compayré's *Elements of Psychology*, pp. 76, 196, 197.

brings with him into the world. We then recognize what capital he has inherited from his ancestors, how many phenomena his mind displays which are independent of sensitive impressions, and how erroneous it is to think that man learns to think, to feel, and to will by himself, simply by the mere activity of his senses."[1]

From this it follows that the teacher, to succeed in his work, should take care to discriminate these general tendencies of nature,—for example, curiosity, desire for pleasure, sympathy, and self-esteem. He can contribute to the formation of the mind only in so far as he knows how to conform to natural laws; just as the hygienist can assure the health of the body only by adapting his prescriptions to the laws of the living organism.

Difference of Aptitudes.—But the effect of the innate is not merely to furnish all intelligences with a common fund of inclinations which are found in all children. It diversifies minds; it varies its gifts; it endows some with more memory, others, with more imagination; it distributes the substantial qualities of judgment and reason capriciously and in very different proportions. In vain does psychology use every effort to emprison the mobile and variable nature of things in exact and fixed formulas; it does not succeed. There are always individual differences. When psychology has taught you what the child in general is, what human nature is, it still remains for you to learn by your own experience, what, in their distinct individuality, are the children whom you have to educate.

The divination of character, so important in moral education, is no less so in intellectual education. Some children need to be watched continually, constantly held in check; they will make no progress unless you have

[1] Preyer, *L'Ame de l'enfant*, Preface, p. xi, Paris, 1887.

your eye always on them, explain the slightest things to them, and, to use this trivial expression, chew all their food for them. Others, on the contrary, should be allowed to walk entirely alone; they should have free rein. You would impede them, if, through an indiscreet zeal, you should endeavor to direct all their movements. Sometimes there is extreme emulation, and at others almost none. Taste for reading, very strongly developed in some, scarcely exists in others. In short, there are no two children who are alike. It is indispensably necessary to be able to recognize these differences, sometimes slight, sometimes well marked, in order to strengthen the favorable aptitudes and make them serve your end, or to repress and restrain them, if, by their natural exaggeration, they threaten the general harmony of mental development.

Identity in the Order of Succession.—The diversity of aptitudes which obliges the teacher to vary and to graduate his means of education with great ingenuity, in order to meet the wants of each child, does not, however, prevent the organization of a course of study identical for all.

Because, as correctly observed by a writer on infant psychology, individual differences depend much more on the time and the degree than on the order of succession and appearance of intellectual phenomena. These phenomena are essentially identical in all cases.[1]

In other terms, the faculties are not developed in all children of the same age at the same hour; they have not the same degree of power; but they appear one after another in the same order of succession. There may exist sensible differences in the size of fruit, the color of flowers, and the

[1] Preyer, *op. cit.* Preface, p. vii.

dimensions of leaves; but, as a general rule, leaves precede flowers and fruit.

The consequence is that we may, without fear of mistake, offer to all children the same course and gradation of studies, on the condition, however, that we retard or hasten this forward movement, according as we have to do with sluggish, backward, slowly developing natures, or with precocious intelligences, in which some inward power hastens and precipitates the intellectual evolution.

The Gradation of Studies.—In the selection and distribution of studies, then, we will seriously consider the natural sequence of the faculties. The logical order of a good course of instruction should correspond to the chronological order of the development of the mental powers. Just as the stomach of the infant bears no food but milk, and as it would be dangerous to give it solid food until it has teeth to chew it, so the mind of the child admits at first of no other intellectual food than concrete knowledge. It has not the power to digest and assimilate abstract truths and general ideas. Only chimerical idealists, like Malebranche, could imagine that the intelligence is not characterized by age, and that the little child has as much reason as the mature man. As has been clearly established by modern educators, and notably by Mr. Spencer, success in studies is possible only when the instruction begins with the simple and concrete and proceeds to the complex and abstract.

"There is a given order in which, and a given rate at which, the faculties unfold. If the course of education conforms itself to that order and rate, well. If not—if the higher faculties are early taxed by presenting an order of knowledge more complex and abstract than can be readily assimilated; or if, by excess of

culture, the intellect in general is developed to a degree beyond that which is natural to the age—the abnormal result so produced will inevitably be accompanied by equivalent, or more than equivalent, evil."[1]

Knowledge, presented out of season to an ill-prepared intelligence, either yields it no profit, but glides over the surface of the mind which is unprepared, just as seed is lost on an untilled field; or, on the other hand, though more rarely, this precocity of forced studies provokes an artificial excitation which fatigues and exhausts the intelligence in its prime and makes it sterile forever. Infant prodigies rarely become distinguished men, unless their extraordinary growth be the result, not of an excessive and abnormal culture, but of extraordinary natural endowments.

Curiosity.—The fundamental principle, then, of a sound intellectual education, is to regulate the order of studies and the choice of methods according to the natural laws of the mind's spontaneous activity. To this end, the teacher should constantly appeal to the instincts of the child, "those inclinations of nature which, as it were, anticipate instruction,—and especially curiosity."

Curiosity is one of the chief springs of the intelligence, but it is a delicate spring which is easily broken if not prudently and skillfully handled. Curiosity, generally very active in a young child, is often blunted, and sometimes disappears in the scholar because we do not know how to sustain and exercise it.

"The manner in which a child is instructed," says a shrewd observer, "often has the disadvantage of forestalling curiosity, of preventing its rise, or, at least, of promptly arresting its move-

[1] Spencer's *Education*, p. 268.

ments. In fact, what do we do? We take a child, seat him on a bench, and teach him a multitude of things of which he has never observed the existence, which he did not anticipate, and which, consequently, he could not desire to know. We destroy his curiosity before it has had a chance to be aroused. As to the things of which he has been able to catch some glimpses, and which, perhaps, have puzzled him, we bring these before him completely and all at once, and even with greater detail than he requires. We overtax his curiosity almost before it is born. We teach him so many things by compulsion, which he no longer has the least desire to know."

There is, then, a special art in keeping curiosity aroused, and he uses this powerful means of education to best advantage who does not abuse didactic instruction, but interests the child in seeking and discovering truth for himself.

Self-Love.—All children are endowed with curiosity. All are, also, more or less sensible to self-love. Whatever may be the possible abuses of emulation, we do not think that intellectual education can do without this stimulus. Doubtless the child desires to know; but, in addition, he desires to know what his companions do not know, or, at least, to know it better than they; and it is the teacher's duty, while moderating them, to take advantage of these little ambitions for study.

Just as in morals it would be unwise not to grant well regulated interest as an auxiliary to duty, so in pedagogy it would be dangerous not to add the stimulus of self-love, however egoistic it may be, to the disinterested love of learning.

Intrinsic Charm.—It would be utterly to disregard the laws of human nature, and to forget the unity of the moral

organism, to suppose that the faculties of the intelligence alone should coöperate in the work of intellectual education, and that it is not necessary to blend the sensibility, under all its forms, with the occupations of the mind.

In this respect we have given up the prejudices which prevailed during the period of asceticism, when Pascal was led to renounce the study of geometry as a sin, because it was agreeable to him. Without going so far as to say, on the contrary, that a study is good, that it can benefit the mind, only on condition of its being agreeable or giving pleasure, it is certain that we should, as far as possible, eliminate from instruction its asperities and useless rigors, and render it in some measure attractive.

And this attraction will result, not so much from foreign embellishments and vain attempts at agreeable artifices, as from an exact adaptation of the study to the age of the child, and from our own efforts to select and present the subjects of instruction in the order and manner which will be most interesting to the pupil. It is a psychological law, indeed, that all activity is agreeable which responds to the forces of human nature and is in harmony with its laws.

Necessity of Effort.—But however much disposed we may be to recognize the advantages of attractive study, we shall not say with Fénelon: "Pleasure must do everything." In his exceedingly complacent system, the author of *The Education of Girls* repudiates whatever is painful. He wishes in all things to substitute pleasure for effort. He does not dare to present to the child knowledge wholly unadorned and dry, for fear of repelling his attention; he must always adorn it with artificial attractions. He absolutely proscribes didactic instruction. In the pursuit of

knowledge he follows none but pleasant paths, and in training the mind uses only agreeable processes.

Seductive but dangerous utopias, which disdain the persevering and sometimes painful efforts exacted by intellectual education! Doubtless it is well and even necessary not to discourage and disconcert the child's mind, especially in the beginning, by instruction that is too grave or too austere. But through a desire to render studies attractive, we diminish their power, render them puerile, and compromise their wholesome and strengthening effect. Through the desire to extenuate the weakness of the child, we take the most direct means to perpetuate this weakness. The true way to make the child strong intellectually and morally is to believe in his natural power, to give him credit for even more power than he really has, and in all cases to call into exercise what he has, without sparing him either the pain or the fatigue coming from its use.

Intellectual education is not merely the result of the natural and normal development of the intellectual faculties proper, aided and guided by the skill of a teacher. We have seen already that sensibility plays a part in the work, and what we have just said of the necessity of effort proves that intellectual education is also in part a work of the will. We should lose our time and labor, should have organized in vain the best methods of instruction, and in vain should have sought auxiliaries in curiosity, self-love, and sensibility, if we did not know how to awaken in our pupils a strong determination for self-instruction.

Application of the Faculties to the Different Orders of Knowledge.—We see, then, how the different faculties of the soul are brought into play in intellectual education. It is none

the less true that the teacher should give his special attention to the particular powers of the intelligence. He should know how to excite all of them, should guard against favoring one to the exclusion of others. Education is not a series of special cultures, but is an harmonious development. The field of studies for the primary school, although restricted, is sufficiently large to give play to the several mental aptitudes of the child. There are some studies which demand special exercise of the memory, others of the reason, and still others of the imagination. By a clear insight into the nature of the work to be done, the educator should know just what instruments, what intellectual tools he should use in any given case. Just as he should forget no one of the little band of children which he is leading, and as he is not allowed to leave any one of his pupils inactive and neglected at his seat, so in this aggregate of faculties which constitute the mind, there is not one which he should not in its proper time bring under discipline by inciting it to the exercise adapted to it.

The important thing in intellectual education is not so much to impart a vast amount of knowledge as to create a taste for self-instruction, and to form the faculty for acquiring and elaborating. We may say of all the intellectual powers what Diesterweg said of attention : " Attention is a precious faculty : the mind may forget what it has learned, but the faculty of being attentive, once acquired, is never lost."

SUMMARY.

26. Intellectual education has a double purpose : to furnish the mind and to form it.

27. The primary school evidently has not at its disposal so many means for the development of the intellectual

faculties as have the schools for secondary and higher instruction; yet, limited as is its instruction, its work may and should have an educative value.

28. The essential thing is not so much what we teach as how we teach it.

29. To teach successfully, we must, first of all, know thoroughly what we teach, but we must also know: (1) how to conform to the progressive order of the development of the intellectual faculties; (2) how to take into account the nature of the different branches which compose the curriculum of studies, so as to apply, in the pursuit of each study, the faculties which are adapted to it.

30. The intellectual faculties, like all natural forces, are subject to the laws of development, of progressive evolution.

31. The mind is not a *tabula rasa* at birth; it possesses innate aptitudes and tendencies. The teacher should be able to discern both the general inclinations which constitute the common basis of human nature, and the special aptitudes which distinguish the individuals.

32. Individual differences depend more upon the *time* at which intellectual phenomena appear and on the degree of their power, than on the order of their sequence.

33. There is in the development of the faculties a constant sequence, to which should correspond the gradation of studies and the choice of methods. The logical order for the course of instruction corresponds to the chronological order of the evolution of the faculties.

34. The teacher should know how to appeal to the instincts of the child, those natural tendencies, which, it has been said, anticipate instruction, namely, curiosity and self-love.

35. The intellectual faculties are not alone concerned in intellectual education: it is necessary to put also under

contribution the sensibilities, the natural demand for pleasure, and, consequently, to render instruction agreeable and attractive.

36. Intellectual education is, in part, a work of the will; it would be dangerous always to substitute attraction for effort. The child's powers must be exercised, sparing him neither pain nor fatigue.

37. All the intellectual faculties should, in turn, be exercised and applied, each in its own time, to the different subjects of study, according as they demand more of memory and imagination, or of judgment and reason.

CHAPTER IV.

INTELLECTUAL EDUCATION.—EDUCATION OF THE SENSES. EXERCISES IN OBSERVATION.

The Senses and Intellectual Education.—In a well formed mind, whose intellectual education is complete, each faculty should have been exercised and developed so as to contribute its part to the common work, which is the ability to think well; just as in a family, or in a well ordered state, each individual works in his sphere, contributing according to his ability to the collective prosperity of the family or nation. The ideal, then, for this solidarity of function, which, by a single word, we call intelligence, is a special adaptation or special culture of each faculty in question through the knowledge which it has acquired or is capable of acquiring, and thereby capable of being associated in the harmonious action of the whole.

Consequently, active and alert senses which furnish us with accurate and definite perceptions; a clear and reflective consciousness; a prompt and faithful memory which preserves all the acquisitions of experience; a vivid imagination; an accurate judgment and a sound reason, correctly founded on well conceived general notions; such, in short, is a list of the intellectual qualities which the teacher should assure to his pupil, in order to obtain a happy equilibrium of all the faculties.

Education of the Senses.—The senses play too great a part in the organization of the intelligence for us to allow

them to be neglected, as was done by the old education. Formerly the child's eyes were scarcely exercised at all, save as they were fixed on a book, or on the letters of the alphabet. To-day we tax our ingenuity to present to them all sorts of sensible objects, or, in default of objects, pictures.

The education of the senses, which, in fact, begins at the cradle with the first look the child casts upon the world, should be the object of the attentive solicitude of parents; but this process is continued at school. Moreover, it comprises several parts, the senses themselves being complex organs, the material instruments of intellectual perception.

1. The first essential is to assure the natural health and integrity of the organs, and to preserve them from the infirmities which interfere with their normal function.

2. Then each sense should be so perfected by appropriate exercise, that in its own sphere it may acquire the greatest possible power and precision.

3. While we are developing the senses themselves, we should also develop those active faculties which coöperate in their exercise, as attention, or the habit of observation.

4. And lastly, the senses being the material conditions of all ideas, and of all feeling of the beautiful, it is not useless by the choice of the perceptions which we suggest to the child to pave the way for his æsthetic education, that is, to accustom him to enjoy the beauties of nature and art.

Hygiene of the Senses.—The starting point in the education of the senses is found in physiology and hygiene. The senses, being extremely delicate organs, are sometimes imperfect in their natural structure; and through lack of

care they contract other imperfections. To speak only of the eye, the most important of all the senses, myopia is the unmistakable evidence of this effect of a bad education.

In fact, myopia is often the consequence of the conditions of school work. The proof of this is the fact that the number of pupils affected with it sensibly increases from grade to grade. Of one hundred and six pupils examined in the first year of the primary department, not one was near-sighted; of sixty-six pupils in the high-school department of the same school, eleven were near-sighted.

Specialists agree in attributing this alarming increase to a prolonged unwholesome posture. Pupils hold their eyes too near their books and tablets; and this is because the lighting is defective, the school furniture badly arranged, the books too finely printed, or because the methods of writing are bad. The cause of the evil being known, it is easy to find the remedy. Hygienists state that, as a rule, "the distance of the eyes from the book should never be less than 25 centimetres in the kindergarten, and 33 centimetres in the primary school."[1] Moreover, they give a multitude of minute regulations, which we shall simply summarize.

Lighting of Rooms.—The problem of lighting a class-room is solved when there is sufficient light in the darkest place. Bilateral lighting is better than unilateral lighting. In kindergartens especially, lighting by sky-light is best.

Furniture.—The distance apart should be such that a line dropped from the top of the desk would touch the front of the seat; the desk should not be too high; the pupil should be able while writing to support himself against the back of his seat; his feet should rest on the floor; and lastly, the top of the desk should be slightly inclined.

[1] See *Hygiène des Écoles Primaires*, Rapports et Documents.

Still other conditions are required, the details of which would lead us too far out of our way. These relate to the position of children while writing, and to text-books, whose type should not be too small, and which should be printed on white, or better, yellow-tinted paper.

Doubtless, these rules could not always be observed, but it is well to indicate them, in order to encourage instructors to conform to them as far as possible. For who would willingly permit his school to become a manufactory of near-sighted children?

The Perceptions are Perfectible.—It would be to no purpose for nature or hygiene to have given us excellent instruments of sense-perception, unless we had learned to make use of them. Like all the faculties, the senses are perfectible. There is a considerable margin between what they are naturally and what they are capable of becoming by means of a systematic and regular education. As Rousseau has said, "we can neither touch, see, nor hear, save as we have been taught." Take the most intelligent child, naturally endowed with good sight; it remains still to teach him how to see, how to consider an object under all its phases; it remains to give him the habit of precise, complete, exact perceptions, which are not satisfied with a rapid glance or a superficial consideration of things, but which patiently analyze all the details and all the particulars of the objects perceived.

The Senses as Instruments of the Mind.—What should particularly interest us in the education of the senses is that it is not simply a matter of putting them in condition to provide with certainty and promptness for the wants of the material life. While we are exercising them for them-

selves, as for example, when we teach the eye to measure distance, or to explore at a single glance all the aspects of a given object, we are storing up material for the mind. Sense-knowledge is not only the most abundant, but it is also the first that the intelligence can acquire, and that which should serve as the basis of all other knowledge. In 1762, before the time of Pestalozzi and Froebel, La Chalotais wrote that "the fundamental principle of all method is to begin with what is sensible, so as to pass gradually to what is intellectual"; and at the same date, Rousseau developed the same thought in the *Émile*. Before either of them, Comenius had said that the principle of education was that one should "see and name."

Teaching through the Eyes.—It may be said that the greatest innovation of modern pedagogy consists precisely in this tendency, more and more manifest, to substitute for abstractions, general rules, and lessons learned by heart, sense-intuitions, or concrete perceptions. And if we will consider the matter closely, this pedagogical revolution has taken place to the special advantage of a single sense, that of sight. The characteristic of modern methods of intellectual education is, that they are, so to speak, a substitution of the eye for the ear. Horace Mann expresses it clearly in the following passage:

"After the earliest years of childhood, the superiority of the eye over the other senses, in quickness, in precision, in vastness of its field of operations and in its power of penetrating, like a flash, interstices where light can go and come, is almost infinite. The senses of taste, and smell, and touch seem to be more the servants of the body than the soul; and, amongst the infinite variety of objects in the external world, hearing takes notice of sounds only. . . . . But the eye is the great thoroughfare between

the outward and material infinite and the inward and spiritual infinite. The mind often acquires, by a glance of the eye, what volumes of books and months of study could not reveal so livingly through the ear. . . . To use the ear instead of the eye, in any case when the latter is available, is as preposterous as it would be for our migratory birds, in their overland passage, to walk rather than to fly."[1]

Exercises in Intuition.—In intellectual education, then, exercises in intuition ought to take more and more the place formerly given to the mechanical exercises of memory. This necessity gave rise to the system of *object lessons.* Instead of words transmitted through the ear to the memory, things themselves are presented to the mind through the eyes.

As Mr. Spencer puts it:

"The saying of Bacon, 'that physics is the mother of the sciences,' has come to have a meaning in education. Without an accurate acquaintance with the visible and tangible properties of things, our conceptions must be erroneous, our inferences fallacious, and our operations unsuccessful. The education of the senses neglected, all after education partakes of a drowsiness, a haziness, an insufficiency which it is impossible to cure."[2]

Object Lessons.—Object lessons do not profess to take the place exclusively of sense-intuitions, intuitions which the teacher may find a thousand occasions for exciting in the different parts of his instruction; nor of the spontaneous observations which the child is called to make at every instant in his walks and his recreations, any more than gymnastics professes to take the place of free sports and instinctive activity, in the education of the body. But

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[1] Horace Mann, *Lectures on Education.*

[2] Spencer's *Education*, p. 62.

there is a gain nevertheless in having object lessons as a distinct exercise, especially in the beginning of studies. Children, with their native curiosity, are easily prompted to look and to observe for themselves; but their observation is weak, it is fickle, it lacks patience and perseverance. Hence the utility of *object lessons*, which, in reality, are but examples, given by the teacher, of the manner in which an object must be observed if we would take account of all its sensible qualities. The object lesson regulates, so to speak, sense-intuition; it gives method to the exercise of the senses. It is of less value for the particular knowledge which it imparts concerning the object which serves as a text for the lesson, than for the general habits which it tends to form. When the child, under the direction of the teacher, shall have several times analyzed a given object, as a plant or a mineral, under all its phases, he will have corrected the natural mobility of his intuition; he will have acquired a disposition to proceed in the same manner, that is, with order and method, in the course of all his studies as well as in his personal observations.

The True Method to Follow.—It goes without saying that the object lesson, which is an appeal to the senses and to the activity of the mind, to be effective, should not be transformed into a prolonged, mechanical, and consequently irksome, exercise. Pestalozzi made this mistake when he had his pupils repeat for hours what they observed in the mysterious wall-paper, whose rents they laboriously described . . . .

As Buisson very judiciously observes in the *Dictionnaire de pédagogie* (article *Intuition*): "When we have had children study a ruler, a cube, a table, a door, or a stove, for two or three lessons in succession, under pretext of impressing

upon them by successive exercises the intuition of the several physical or geometrical qualities of this object, we no longer obtain from them anything but words; they will repeat in chorus, if desired: 'The table is rectangular,' or 'the ruler has six faces and eight corners;' but they will turn their heads, think of something else, and will no longer care to see either these faces or corners. It is sufficient for them to have made these observations once or twice; all the repetitions which follow can be but mechanical."

The object lesson can be useful only on condition that it be interesting and attractive, consequently that it be judicious and moderate, and that it do not renew, under another form, the faults of ancient methods.

We can not repeat too often, that the purpose of the object lesson, in presenting to the senses of the child material objects, systematically chosen and carefully graduated, is not so much to have him perceive methodically the several qualities of these objects, as to give him the habit of adopting this method of analysis and complete observation in all his perceptions. The purpose is to teach him to discriminate with accuracy colors and shades of color, and to judge of length or distance. The purpose is to develop what the great painter, Leonardo da Vinci, calls "accurate judgment by the eye," or as another illustrious artist, Michael-Angelo, has said, "to put the compass in the eyes."

The purpose is to prepare for the whole course of life an exact and penetrating power of perception, which may serve as a mental photography of material reality, which may permit the mind to accumulate a series of clear and exact images, and which, in a word, may make the senses the instruments of a kind of instinctive and natural geometry.

Drawing.—It is not only in formal object lessons, but also in the most of what is taught in school: in writing, drawing, elements of the physical and natural sciences, geography and manual exercises, that the teacher will be concerned in the education of the senses.

Rousseau had already pointed out the importance of drawing, as an instrument for the education of the eye:

"Children, who are great imitators, all try their hand at drawing. I would have my pupil cultivate this art, not exactly for the art itself, but for rendering the eye accurate and the hand flexible; and, in general, it is of very little consequence that he understand such or such an exercise, provided he acquire the perspicacity of sense, and the correct habit of body, which are gained from the exercise. I shall take great care, therefore, not to give him a drawing-master who will give him only imitations to imitate, and will make him draw only from drawings. He shall have no master but nature, and no models but objects. He shall have before his eyes the very original, and not the paper which represents it; he shall draw a house from a house, a tree from a tree, a man from a man, so as to become accustomed to observe bodies and their appearances correctly, and not to take false and conventional imitations for real imitations I shall discourage him even from tracing anything from memory in the absence of objects, until, by frequent observations, their exact figures are firmly impressed on his imagination; for fear that, substituting odd and fantastic forms for the truth of things, he lose the knowledge of proportions and the taste for the beauties of nature. I am well aware that in this way he will scrawl for a long time without making anything that is recognizable; that he will be late in catching the elegance of contours, and the light touch of designers, and perhaps never a discernment of picturesque effects and good taste in drawing; but, by way of compensation, he will certainly contract a juster glance of the eye, a steadier hand, a knowledge of the true relations of volume and form existing in

animals, plants, and natural bodies, and the more ready use of the play of perspective." [1]

Drawing is, beyond question, the best gymnastics for the sense of sight. In the *Instruction spéciale sur l'enseignement du Dessin,* published under the direction of the minister of public instruction, it is justly maintained that to learn to draw is at the same time to learn to see and to note what is seen. Consequently, it is required that in the kindergarten, and even in the primary school, instruction be given in drawing in connection with the object lesson; in fact, the description of an object could not be better given than by a representation, by a drawing. To have the child describe verbally an object which you may present to him is well; but to put a pencil into his hand and exercise him in reproducing it on paper or on a slate, is still better.

Manual Exercises.—There is scarcely an exercise of the school that may not be adapted to the education of the senses; but without dwelling on all the subjects of instruction, we shall emphasize briefly, from this point of view, the importance of manual exercises.

As Monsieur Schmitt expresses it in his *Pédagogie du Travail Manuel,*[2] the effect of the exercises of the school workshop is not merely to develop the dexterity of the organ of touch, the hand, which Gratiolet called "the five-pronged compass," but also to perfect the eye, to train it in estimating magnitudes.

"Let us suppose a child occupied in reproducing a box 30 centimetres long, 10 centimetres broad and 4 centimetres high. He will have the dimensions constantly before his eyes; will compare them with one another; they will be photographed in his

[1] Rousseau, *Émile,* book II.

[2] *Pédagogie du Travail Manuel,* by E. Schmitt. Paris, 1889, p. 70.

mind, and it can not be doubted that after this continued and reflective observation, he will be able to mark off from memory and without hesitation, the lengths 30, 10 and 4 centimetres with remarkable exactness, and by comparison, the double length, the half and the quarter. The same will be true in the case of surfaces and volumes."

Culture of the Attention.—The benefit derived from the education of the senses is not confined to the senses themselves: this education benefits the mind by furnishing it with innumerable ideas, and again by exercising those intellectual functions which are necessarily involved in the exercise of the senses, notably attention.

Train the child to examine sensible objects with care, to study the structure of the flower or the organism of an insect in all its details; not only do you teach him to see accurately, but you will have given him besides the habit of attention. And this power to concentrate his mind and to apply it to whatever he wishes, when once developed for the sake of material things, will always remain, and will come to be applied progressively to things in general.

Nothing is so delicate or so fragile as the attention in its first manifestations. If you employ unskillful methods, if, for example, you seek by force to hold the child's mind on books which do not interest him, or on abstractions which he hardly comprehends, you run the risk of rendering him inattentive for life; you provoke him to seek in distraction a refuge or defence against the ennui caused by studies illy adapted to his age.

There is then no other way, no surer or easier method of provoking the nascent attention of the child than by presenting to him sensible objects. In studying them he finds a pleasure which he could not derive in the same degree from the most skillfully conducted lessons, or from stories

the most happily related. And attraction or interest, as some one has said, "is an unique talisman for developing the attention."

The Habit of Observation.—Attention directed to external things takes a particular name; it is called observation. And there is an inestimable advantage in the child's becoming, not merely attentive in everything, but also observant; that is, attentive to whatever may be the object of sense. Mr. Spencer does not hesitate to declare that "success in all things depends on the power of observation." What is certain is, that the observation which is at the basis of the physical sciences is also the starting point in practical experience, the condition of success in business. How many errors would we not avoid in our social relations, for example, if we knew better how to observe other men, if we had learned by a penetrating and clear-sighted observation to divine their intentions and to know their characters, which are often betrayed in their gestures, and in facial expressions!

Nature, without doubt, endows every child with an instinctive inclination to observe. But what a difference there is between children in this respect! One will not have spent two minutes in a store-room or an apartment before being capable of describing everything it contains, and with the searching eye of an appraiser he will have seized the most minute details. Another, on the contrary, will have looked a long time, with seeing nothing, or almost nothing. There is reason, then, for being preoccupied, in education, with this inequality of aptitudes, and for favoring the development of the spirit of observation, by making frequent appeals to this faculty, and by obliging the child to render an account, either orally or in writing, of what he has seen.

Hearing and Singing.—The intuitions or observations of sight are certainly not everything in the education of the senses. Touch and hearing also merit the attention of the teacher. Hearing especially needs to be exercised at an early age. To hear well is a precious endowment. To be able to listen is still more important. In short, to have an ear is a desirable thing. The senses, such as hearing and seeing, are not merely the intermedia between the mind and the material qualities of the external world. When cultivated from this point of view, they also reveal the sensible beauties of things. Singing is to the ear what drawing is to the eye—a kind of appropriate gymnastics which develops the musical qualities, and leads to the appreciation of the purity of sounds; just as drawing teaches one to know and appreciate the accuracy and symmetry of lines and the beauty of forms.

The Æsthetic Feelings.—It is thus that the education of the senses lifts the mind of the child above things purely material, and elevates it gradually toward the enjoyments of art. The contemplation of the physical world, provided it be well directed, may be the awakening of the highest emotions. When a child is led to observe the tints of the rainbow, the changing colors of the dewdrop, or the majestic splendor of the setting sun, he is filled with love and admiration for these sights; he comes to comprehend the beautiful, to have a taste for it, and to seek it in order to enjoy it, both in nature and in art.

SUMMARY.

38. Intellectual education supposes the special culture of each faculty necessarily involved, in order that it may concur in the harmonious action of the whole.

39. The education of the senses is complex: 1, we should insure the material integrity of the organs; 2, the perceptions proper of each sense should be perfected; 3, the exercise of the senses should be utilized in developing the faculties which are actively involved in it, namely, attention and the habit of observation: 4, sense-perceptions should be used as the means of awakening the idea and the feeling of the beautiful.

40. The education of the senses depends first on hygiene, which maintains the organs in their normal condition, and, for example, protects the child against *myopia*, which is often the result of a prolonged, injurious posture.

41. The sense-perceptions are perfectible; we learn to see, to touch, and to hear.

42. To educate the senses, they must be exercised; and while exercising them, we are not only rendering them more apt to perceive with precision, but are enriching the mind with a multitude of ideas which are the elements for the further development of the intelligence.

43. One of the principles of modern pedagogy is that we should gradually rise from the sensible to the intellectual.

44. In this pedagogic evolution which substitutes things for words, it is the sense of sight that is especially concerned, it is a question of instruction through the eyes.

45. The object lesson is a systematic exercise in perception or intuition; its merit lies not so much in its imparting any particular knowledge concerning certain objects, as in its forming the habit of observing everything methodically, patiently and thoroughly.

46. Most of the studies of the school offer facilities for the education of the senses, but drawing and manual exercises are of special value.

47. The exercise of the senses benefits the mind also

by offering an occasion for the development of the attention and of observation, which is simply attention directed to external things.

48. We run great risk of arresting the growth of attention, if at first we should forcibly employ it on abstractions; the best way to provoke it is to appeal to it through sensible things, which have a natural attraction for the child.

49. The senses not only reveal the scientific properties of external objects, they also enable us to apprehend the æsthetic qualities of things, and prepare for the subsequent education of the taste for the beautiful.

CHAPTER V.

OFFICE AND CULTURE OF MEMORY AND IMAGINATION.

Simultaneous Culture of the Different Faculties.—If it is necessary to give an important place to the education of the senses, it is not a reason, as Rousseau wrongly asserted, for devoting the first years of childhood exclusively to exercises in intuition. Exercises in memory and judgment should, from a very early age, be combined with the exercises in intuition. What value would attach to the sense-perceptions themselves if they were not controlled by the judgment and retained by the memory?

Moreover, books and oral lessons soon claim their part in instruction, and then all the faculties of the mind find occasion for being exercised, memory and imagination holding first rank.

In learning to read, for example, the child has first to use his eyes; a quick and accurate intuition of the letters of the alphabet will hasten the success of his efforts. But complete and rapid success is possible only as this intuition is followed by a clear representation in the imagination, and a faithful and firm retention in the memory.

In an illustrated reading lesson it is not perception, memory and imagination alone that are called into play; but judgment and reason also are active, however little we may wish the pupil to comprehend the sense and connection of thought contained in the text.

In other terms, the intellectual faculties have in vain

been distinguished from one another by psychological analysis; in fact, they are blended together; and the duty of the teacher is to call all of them into exercise, not one after another successively by a fragmentary culture, but all together and in one common effort.

General Rules.—Francis Naville, a Swiss educator, has clearly summarized the general rules or principles which may be safely followed.[1]

"1. The first principle is that all the faculties should be cultivated."

In other terms, all the faculties have a claim to education; all are capable of improvement, and all should be cultivated. How neglect any one of them, if the purpose be to form a complete mind, in which no important factor should be wanting?

"2. In the culture of the faculties we must regard the natural dispositions of the child, its sex, its vocation, and the relative importance of the faculties."

The faculties do not manifest the same degree of natural energy in all children; hence the necessity for the teacher to vary his methods of instruction and his style of questioning, in order to adapt them to the individual aptitudes of his pupils, tempering the too active imagination of one, and exciting the sluggish imagination of the other. Moreover, the faculties are not all of the same importance; hence the necessity of proportioning exactly to the part which they have to play, the scope which, by particular culture, we prepare for each of them; memory, for example, will be subordinated to judgment.

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[1] See *l'Education publique considérée dans ses rapports avec le développement des facultés, Paris, 1833.*

"3. All the faculties should be educated simultaneously.

"4. Each faculty should be applied exclusively to the objects of its sphere."

Although all the faculties do not unfold with the same rapidity, though some precede others in a natural order of evolution, yet all should, as far as possible, be put under discipline. On the other hand, each faculty ought to be kept in its distinctive sphere: memory, for example, has almost nothing to do with the rational sciences, as arithmetic and geometry.

The Senses, Consciousness, and Memory.—The sense-perceptions are the principal source of mental aliment: the memory is, as it were, the reservoir in which all these perceptions are stored. But it is not sense-impressions alone that are entrusted to the care of the memory. The internal impressions of consciousness, general ideas, in short, whatever has at any time constituted a state of consciousness, has a tendency to reappear in the mind, with greater or less force according as the first conscious state was more or less intense.

The condition of exact and faithful memory is, therefore, the vivacity of the original impressions. You have already done much for the culture of memory when you have provided the child with clear intuitions, and in another sphere, have presented to him none but well explained, and, therefore, well understood, general ideas.

But the culture of the memory should not look simply to the source, or what might be called the roots, of particular memories, whether concrete or abstract. Although Locke maintains, and a whole school of philosophers with him, that there is in the mind nothing more than a series of memories which are lodged there with different degrees of

tenacity according to circumstances; yet there is in reality an aptitude or tendency to recall, which nature or education makes more or less strong; a faculty, not simply for retaining whatever has already been perceived or conceived by the intelligence, but for apprehending other things, and for retaining new knowledge with an ever increasing facility and certainty.

The education of the memory, then, is not concerned simply with furnishing the mind with a great number of recollections; but tends to fortify the memory itself; and the only way to fortify it is to exercise it.

A Page of Rollin. — In the *Traité des études*, Rollin has written a few thoughtful pages on the culture of memory which are worth analyzing in this place.[1]

"Memory," says he, "is the guardian and depository of what we see, of what we read, and of all that our teachers, or our own reflections, have imparted to us."

Rollin then observes that a good memory is at once the gift of nature and the result of effort. From this he infers that it is very important to begin the cultivation of memory in children at an early age. But he is wrong in adding that "in their tender age they are as yet capable of hardly any other effort," forgetting that at least sense-perceptions, object lessons, and exercises also in illustrated reading, in writing and drawing, are equally well adapted to the capacity of children.

Rollin is next occupied with memories that are naturally sluggish and restive, which at first refuse all service and seem condemned to utter sterility.

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[1] See the *Traité des études*, book II, *de l'Intelligence des langues*, chap. III, art. 4: *De la nécessité et de la manière de cultiver la mémoire.* This study does not appear in the first edition of the *Traité.*

"We must not be easily discouraged," says he, "nor yield to this first resistance which we have often seen conquered and mastered by patience and perseverance. At first give a child of this nature a few lines to learn, but require him to learn them exactly. Try to sweeten the bitterness of this first effort by the incentive of pleasure, offering him none but agreeable things, such, for example, as the fables of La Fontaine, and thrilling stories."

One could not better point out the necessity of proceeding with care, of guarding against making the pupil's first lessons too heavy, of selecting for recitation easy and attractive texts.

Memory and the Intelligence.—Rollin did not forget that the memory needs the coöperation of the intelligence, that is, of the judgment; that therefore we must not be satisfied with having words repeated mechanically; that the child ought to understand the thoughts expressed, and should thoroughly comprehend whatever he acquires.

"A general rule," says Rollin, "is to apprehend clearly and understand thoroughly whatever we wish to learn by heart. The intelligence certainly does much to aid and facilitate the memory."

Repetition.—It is no less true that there is in memory something of the mechanical, so to speak; an element of mechanical routine. By reason of this element, the most useful of all mnemonic devices is repetition. A single reading of what one wishes to learn by heart does not suffice: the reading must be repeated. In this way the images are more deeply impressed on the mind. It is necessary also, after a few days, to review what has been learned.

The *Conduite des écoles chrétiennes*, which is the pedagogical manual of the schools of the Christian Brothers, gives some practical advice on this subject which we transcribe:

"To read a lesson from beginning to end, then begin anew, reading over and over, is not a good way to study, but rather to pursue the following plan:

1. Read the text two or three times with close attention·

2. Commit to memory one or two lines;

3. When these are well committed, learn as many more, and add them to the preceding;

4. When, by this means, one sentence has been learned, repeat it several times without looking at the book, and pass to the next to study it in the same manner."[1]

With repetition are connected the analogous processes, reviews, summaries and recapitulations, in the case of things that have to be retained without being learned by heart. Have the pupil review what you have taught him, condense it into a brief summary, or reproduce it in equivalent terms. Lasting recollections are not established at the first effort; to fix them, the impression must be renewed more than once. Memory, at bottom, is but an intellectual habit: the acquired tendency to think again what has already been thought. Like all habits, it grows strong by the repetition of the act.

Things Which Should be Learned by Heart.—With whatever discredit certain modern educators presume to cover verbal memory, or what has been called rote learning, it is impossible in instruction to do without the old process which consists in requiring things to be learned by heart. This has been abused, it is true, and in two ways, either by excessive verbal recitation, or by requiring literal memory in studies where it is not concerned; but its use must not for this reason be renounced.

[1] *Conduite à l'usage des écoles chrétiennes*, edition of 1877, p. 17.

Beside the exercise of recitation proper which pertains to quotations from authors, or bits of prose or poetry with which it is well to adorn the child's memory, there are in every department of instruction things which call for the use of literal memory, for example, dates in history, definitions and technical terms in geography, rules in grammar, formulas in the physical sciences, and certain precepts in morals. Even in the purely rational sciences, definitions and theorems, once explained and demonstrated, should be learned by heart. We agree with Mr. Spencer that it is not bad to teach the multiplication table by the experimental method; but we defy anyone to stop at this and exempt the child from learning it by heart.

The only thing to proscribe is the unsound practice which consists in the belief that to repeat words correctly is sufficient, that to understand them is unnecessary. In truth all those educators who have decried the memory are found to have condemned only the bad methods which employ at random the most precious of intellectual instruments.

Prejudices Against the Memory.—It is not the memory then, in its legitimate and necessary office, which can be attacked; it is only the abuse that is made of it in permitting it to encroach on the territory of other faculties. See, for example, what Naville says of it:

"In the education of children the memory usurps a prodigious place, to the great detriment of their intellectual and moral interests. It ought to be confined exclusively to the modest rôle of depository and conservator: to entrust to it a succession of reasonings and sentiments before having submitted them to the discernment of the faculties which ought naturally to take cognizance of them, is to invert the order of things."

In other terms, the memory exercises a bad influence only when it deviates from its function, when it impedes the action of the other faculties. Maintained in its proper functions, it renders the greatest services to the mind; and it is always, notwithstanding its detractors, the pedagogic faculty par excellence, that of which Mr. Bain was able to say that there is none which plays a more important part in education.

Relation of Memory to the Other Faculties. — The memory, in fact, is not merely the servant of words, the passive instrument of literal recitation: it is a living faculty which may be developed in all directions, in behalf of words, doubtless, but also in the service of ideas.

It is not sufficiently noted that a good memory supposes the development of most of the other faculties. In the well formed mind it is a witness which attests that all the other functions of the intelligence are regularly exercised. It is dependent on the sensibility: insensible souls have almost no memory. On the contrary, a child whose affections are active, who takes an interest in things, receives from everything which affects him a profound impression which is a guaranty of a long remembrance. So also the memory depends, not only on the judgment, but on the reason, on the order and the method which we give to ideas.

"It is indisputable," said Port Royal, "that we learn with incomparably greater facility, and that we retain much better, what is taught in the true order, because ideas which have a natural sequence arrange themselves much better in our memory, and are revived one by another."

Finally, the memory has need also of the coöperation of the will; it is the attention, the effort of the mind, which for the time fixes our recollections and permits us to recall

them, to bring them back at will under the eye of consciousness. It is not merely by a special culture, but by developing the sensibility, the higher faculties of the intelligence, the energy of the will itself, the entire soul, in a word, that we shall effect the education of the memory. It has its full force only in well-ordered minds, in souls whose general health is maintained by wise direction. We have all experienced the fact that, when fatigued by any over-exertion, our impressions have lost their freshness, our memory no longer manifests its ordinary facility for apprehending, nor its promptness in recalling.

Mnemonics.—Volumes, treatises of several hundred pages, have been written on mnemonics, that is to say, on the art of facilitating the operations of the memory.[1] Doubtless, with the artificial processes of mnemonics, we may accomplish wonders. The Abbé Moigno, an adept in this art, relates that he succeeded in astonishing the savant, Francis Arago, by reciting to him from memory the altitudes of the principal mountains of the globe. But however ingenious the systems proposed by the specialists in mnemonics may be, and whatever services they may be able to render in given cases, as when, for example, we have a hurried effort to make in view of an examination, all the artificial means, the conventional relations, which mnemonics hold in honor, are to be mistrusted. The memory is not strengthened by everything that aids it. To take another example, the use of written notes, the employing of this "paper memory," of which Montaigne spoke, may aid us in assuring the conservation of a series of particular recollections; but the general culture of the memory is not at all

[1] See, for example, *Principes et Applications Diverses de la Mnémotechnie*, Paris, 1833.

improved in this way; and what is especially important is, first of all, a memory which is self-sufficient, which is founded on real relations, on the natural association of ideas, on the method and logical order which are introduced into instruction, and which has no need of external support, and of purely mechanical processes.

Culture of the Imagination.—Imagination, in its lowest form, is only a higher degree of memory, a vivid representation of what constitutes the object of memory. It is evident, therefore, that in the interest of memory itself we should cultivate the representative imagination.

In reading, writing, drawing, and in exercises of orthography, that child will succeed best who has the greatest aptitude for representing to himself the image, either of the characters of the alphabet, or of the letters of which the words are composed, or of the objects which he draws. It has been justly said that to know orthography is simply to possess the image of words.[1] In literary composition, also, especially in narration, representative imagination will be of some assistance.

The only way of cultivating the representative imagination is through the careful education of the senses. The image is, in fact, only the residuum of a clear and distinct intuition which is preserved in the mind and which remains after the disappearance of the object which provoked it.

Imagination in the School.—But imagination soon disengages itself from this first inferior form. It becomes the active or inventive imagination, which either of itself combines intuitions, recollections and ideas, in order to con-

[1] See the work of M. A. Chaumeil, *Manuel de Pédagogie Psychologique*, p. 88.

struct a story, or a fable, or which at least takes a part in poetical and dramatic compositions, and in all the creations which proceed from an effort of the imagination.

There are then two elements in the culture of the imagination, thus understood: on the one hand, children should be inspired with a taste for poetry and art; on the other, though in a measure which can not be very great in the primary school, they should be exercised in composition, in original creations.

Nothing is more suitable to the mind of the child than this twofold work. The ancient educators were wrong in excluding the imagination from education. In the seventeenth century it was considered simply as an instrument of error. It was not yet recognized that the imagination has its appointed place in the intellectual economy, that it is dangerous only when it goes astray, when it is not regulated, and that the true way of regulating it is to nourish it and exercise it. In our time, people appear to be more just toward the imagination; but as the positive tendencies and scientific tastes tend to predominate more and more, it becomes more necessary than ever to give special attention to the development of a faculty which finds its satisfaction in lofty contemplations and in the creations of art.

Imagination and History.—It is especially by the reading of bits of poetry, of stories and well chosen romances, that the fire of the imagination is kept up. But even history with its characters and stirring narrations is also a school of the imagination.

A great Russian writer, Count Tolstoi, who, after having written admirable novels, has interested himself in pedagogy, claims that history can interest the child only because it appeals to his imagination.

"I am convinced," said he, "that all the characters, all the events of history, interest the pupil, not by means of their historical significance, but on account of their dramatic attraction, by reason of the art displayed by the historian, or more often by popular tradition. The history of Romulus and Remus is interesting, not because these two brothers founded the most powerful city in the world, but because it is attractive, pleasing, wonderful. In a word, the child does not have a taste for the history itself, but for the art." [1]

It does not follow from this that the teaching of history can forget its first duty, which is truth and accuracy; but without ceasing to be accurate, history may interest the imagination if we know how to make it, as Michelet expresses it, "the living resurrection of the past."

Literary Composition.—Let us then nourish the imagination of the child with noble images taken either from real history or from the purest inventions of human genius. But let us not think that our task, even in the primary school, is confined to this somewhat passive education of the imagination. To this must be joined a sort of active education, by discreetly exercising the pupil at brief efforts in literary composition. To get pupils to acquire a taste for this exercise and to succeed in it, is not, perhaps, so difficult a task as is generally believed. Count Tolstoï, in the work we have just quoted, tells us that whenever he would offer to relate any events to the pupils of the school at Yasnaia Poliana, all would become as joyous as if they had received a present. According to him, instructors are deceived when they choose for the subjects of early composition the description of an object, as a table or a bench, for example; he maintains, and not without reason, that

[1] Tolstoi, *L'École de Yasnaia Poliana*, p. 265.

those descriptions which bring into play only the representative imagination interest the child much less than the relation of a story. "The same pupil," says he, "who weeps over having a bench to describe, will give ready expression to a sentiment of love or hate, the meeting of Joseph with his brethren, or a quarrel with his schoolmates. Doubtless, exercises in composition involve other faculties than the imagination: they demand judgment and some reason; but they would always be useful, even though they could contribute only to the development of the imagination."

SUMMARY.

50. To the exercise of sense-intuition should be joined at an early hour the exercise of the memory and the exercise of the judgment.

51. All the faculties should be cultivated at the same time, taking into account, it is true, their relative importance, and also the natural dispositions of the child.

52. Whatever tends to intensify the initial impressions, whether perceptions, general ideas, or any other states of consciousness, also tends to fix the memory of these impressions.

53. But the education of the memory looks not merely to the conservation of particular recollections: it seeks to strengthen by exercise the faculty itself, that is, the power to acquire new knowledge with a constantly increasing certainty and facility.

54. The exercise of the memory consists at first in the literal recitation of easy, short, and attractive texts.

55. The child should never be required to learn by heart what he does not perfectly comprehend.[1]

[1] If this precept means what the words fairly imply, it might better read as follows: Never allow a child to learn anything by heart. (P.)

56. Memory is a habit, and, like all other habits, grows strong by repetition; hence the importance of summaries, recapitulations, and reviews.

57. Although learning by heart should not be abused, there are in every department of instruction, rules, formulas, definitions, etc., which the child ought to know by heart.

58. All the evil that has been said of the memory is applicable rather to the bad methods which have distorted its true function, than to the memory itself.

59. Besides the memory of words, there is the memory of things, which acquires its full power only in a well ordered mind, and which supposes the exercise of all the other faculties, the sensibility, the logical sequence of ideas, the attention, and the will.

60. No great consideration should be given the artificial process of mnemonics, which gives the memory bad habits, which may facilitate and aid its action, but does not strengthen it.

61. The imagination, under its first form, is only a higher degree of memory: in this case it is simply representative, and the only means of exercising it is through the careful education of the senses.

62. The representative imagination renders educational service in reading, writing, drawing, and exercises in orthography.

63. The active or inventive imagination may and should be cultivated at school in two ways: 1st, children should be inspired with the taste for works of the imagination, as poetry and art; 2d, they should be trained in literary composition, in short original productions.

CHAPTER VI.

OFFICE AND CULTURE OF THE JUDGMENT AND REASON.

Judgment and Reasoning.—The perceptions of the senses and of consciousness preserved by the memory, are, as it were, the materials of the mind; but they do not constitute the mind itself, which uses and arranges these materials, which compares and coördinates them through the performance of its characteristic functions, judging and reasoning.

Judgment is the essential act of the intelligence; and the culture of the judgment is the crowning point of intellectual education.

To judge, in fact, if this word be correctly understood in the general sense which is given it in pedadogy, is to separate the true from the false in all things, in the affairs of practical life as well as in the theoretical researches of science. To have judgment is to avoid false solutions by adhering to the true; it is to show the principal causes of error; it is to possess that accuracy of mind which regulates the opinions and governs the actions of good and enlightened men.

Perceptions and recollections make minds more or less ornate, more or less instructed; but judgment alone really makes the man capable of thinking for himself, of being something more than a faithful mirror of external facts and the echo of other men's opinions. Perceiving and remembering are phenomena more or less passive; but judging is

to act intellectually. It is in judgment that the true activity of the mind manifests itself.

In this sense, we see that judgment is rather an aggregate of qualities or a habit of mind than a special and distinct operation. We no longer have to do with that spontaneous judgment to which even the simplest perceptions give rise. To see an object, in fact, is to judge that that object exists. The judgment of which we are speaking differs from this lower form of intellectual affirmation, in that it supposes a work of the mind—the comparison of several primitive judgments, the intervention of general and abstract ideas.

Pedagogically, the judgment and the reason are scarcely distinguishable, and in fact it is not impossible to prove that every judgment supposes a beginning of reason. They may then be united under the common name of the mind's active and reflective faculties.

Culture of the Judgment.—That the culture of these faculties of reflection is the most important thing in intellectual education, is a fact which is to-day universally recognized. The most belated in the old methods are the first to acknowledge it.

"Elementary instruction," says the latest edition of the *Conduite des écoles Chrétiennes*, "has assumed at the present day a particular character of which we must take account; proposing as its principal end the forming of the pupil's judgment, it gives less importance than heretofore to the culture of the memory. Above all it makes special use of methods which exercise the intelligence and lead the child to reflect, to account for facts, to pass from the domain of words into that of ideas."

For three centuries, it may be said that the culture of the judgment has been the watchword of French pedagogy.

Montaigne and the Education of the Judgment.—Montaigne was the first to set the example, and to throw into relief the preeminence of the judgment in the aggregate of the faculties which education seeks to form. In his view, a "well formed head" is worth more than a "well filled head;" in other terms, a sound judgment is worth more than an encyclopædia of knowledge. In history, for example, the important thing is not so much to know the facts, as to be able to account for them; not "to know where Marcellus, the Roman general, died, so much as why it did not behoove him to die there." In everything the child should be accustomed to discover the truth for himself; he will often be shown the way, but occasionally will be left to find it. He will be required to render an account, not of words merely, "but of their sense and substance." That which we desire him to learn, we will cause him to state "in a hundred forms, in order to be sure that he has made it really his own." We will impose upon him nothing "by simple authority:" we will appeal to his independent examination. We will not undertake simply to lodge in his head opinions blindly accepted and admitted for true without being tested. We will propose to him ideas, "money borrowed from others," only that he may assimilate them: he will transform and fuse them so as to make of them a product entirely his own, that is to say, his judgment; to form this judgment is the aim of his instruction, his toil, and his study.

How General Ideas are Formed.—In order to understand well what the education of the judgment should be, we must first consider that abstract or general ideas play an essential part in the operations of the mind which judges and reasons. It is these ideas which serve as the basis for particular judgments.

A good judgment then presupposes, as a preliminary condition, that the intelligence be able to handle with ease abstract and general ideas, and, consequently, to attach an exact meaning to the words which express them. In other words, the first step in the education of the judgment is the acquisition of abstract ideas, and the definition of general terms.

What are the processes which best subserve this purpose? It may be told in a few words, since the tendency of the child to generalize and abstract is much more powerful than is believed, and since it has need only of being aided and sustained in order to manifest itself at an early age.

The first rule is, never to employ with the child, nor allow to pass in a text to be read or to be learned by heart, a single abstract word, without explaining and defining it; and the explanation, of course, should be given, not in other general terms which would themselves need explanation—a thing possible only to a higher stage of intellectual development—but as far as possible in concrete examples, in an enumeration of particular objects of which the abstraction to be defined is, as it were, the *résumé*. For example, you meet for the first time in your lessons the word "science;" do not proceed to say to the child that science is a systematic body of knowledge, that the sciences are different from letters, and also from the fine arts. All these definitions, good for a dictionary, are not good for the intelligence of a child. They require, moreover, a long series of new definitions. No, but appeal to the recollections of the child, recall to his mind the geography which you have taught him, the arithmetic, the history, the physics which he has been studying. Try, by comparing these different sciences, to make him grasp what they have in common and in what respects they are alike; and you will

have succeeded in introducing into the mind of your pupil, in the place of a large unintelligible word, a clear and vivid idea.

Intuition and Abstraction.—The second rule is not to wait till the appearance of an abstract word renders necessary explanations, like those of which we had given an example; but to train the child to discover for himself, by considering the relations of things, the general idea which embraces these relations, and then teach him, if he does not yet know it, the word which expresses this idea. We should apply the method which English educators recommend, under the name of *juxtaposition and accumulation of examples*, and which consists in presenting to the child a series of objects of the same species, in such a way as to call his attention to their resemblances. In a word, we should profit by the natural inclination which leads children to generalize, and then to abstract.

In the first case, the mind of the child goes from the word to the idea which you lead him to understand. In the second, he rises by himself from his particular perceptions to the general idea and the word.

But, in both cases, it is the particular intuition which is the condition of the comprehension of the general idea. To-day we are no longer permitted to present abstractions before perceptions, definitions and rules before examples, words before things. Each general idea, each abstract word, should recall to the child a series of previously acquired perceptions—a body of previous experiences.

Liberty of the Judgment.—Once in possession of a certain number of abstract and general ideas, a child is in a condition to judge and to reason.

But how shall we provoke him to use this faculty, which is to enable him gradually to emancipate his mind, and no longer to limit himself to the servile repetition of what he has learned, but to think for himself?

Just here then are two things especially to be considered: first, by what means personal judgment is to be excited; then, how it is to be regulated. It is necessary, on the one hand, to develop the liberty, the initiative of the judgment; on the other hand, it is necessary to train it, to assure its accuracy.

Too many children who are undismayed in the recitation of their lessons, remain shy the moment a slight effort of individual judgment is demanded of them. All, even the best endowed, are more inclined to reproduce what has been said to them, than to express their own thoughts. We should, doubtless, respect this natural timidity of a mind as yet scarcely formed, which distrusts its own powers, and which but too often finds in its ignorance the excuse for its inaction. Yet, without doing violence to the child, it is well for the teacher as soon as possible to begin in earnest the task of mental stimulation. Let the teacher often interrogate his pupil, and, by questions skillfully graduated, furnish him the occasion of seeking in his little head an opinion entirely his own.

The first original idea which germinates in a child's brain, what a happy discovery! What promise for the future! Here, as in everything else, it is only the first step which costs. And having once entered on this course of original reflection, of intellectual activity, the child will continue, we may be sure, and will, of his own accord, seek to procure again for himself the pleasure which his first effort of invention caused him to experience.

If it is important that the initiative of the child be pro-

voked by multiplied interrogations, it is not less important that he be spared inopportune remonstrances, when, making use of the liberty of his judgment, he ventures injudicious observations, or puerile reflections. It is the teacher who is very often responsible for the inactivity of mind with which he reproaches his pupils. Do they say foolish things? he stops them short, interrupts their speech, humiliates them, discourages them: he stifles forever all inclination to venture the sincere expression of their opinions. Let us be more indulgent: let the child make mistakes at first, provided he thinks. The child would never learn to walk, if he were not permitted in the beginning to make many false steps and even a few falls.

Accuracy of Judgment. — Errors of judgment arise especially from ignorance or lack of attention. We judge incorrectly because we wish to express an opinion of things which we do not know, or because, even knowing them, we are precipitate in our judgments and are too hasty in our conclusions, from following the lead of our tastes and our passions. It is especially among children, naturally giddy and thoughtless, that irreflection is to be feared. This will be gradually remedied by gently showing the pupil the causes of his false judgment. It is not sufficient to say to him that he is mistaken. It is especially important to explain to him in what, and in what way, he is mistaken. By analyzing the error which he has made, he should be made to touch with his finger everything that he needed to know, everything on which he should have reflected, in order to avoid his mistake.

The difficulty, the delicate point is, that it is necessary at the same time to embolden and to correct the judgment; it seems contradictory that one may be able at once to

encourage the flight and correct the faults of this faculty. We reply that it is especially a question of tact and also a question of time. The child's errors may be criticized with discretion and without anger, so as not to discourage him. On the other hand, it is in the beginning especially, and with the youngest children, that it is necessary to excite boldness of the judgment: when the pupil shall once have been accustomed to think for himself, less tenderness may be shown and he need not be spared reprimands and remonstrances.

We have just sketched the picture of the formation of the judgment; let us now see how instruction should be directed in order that it may deserve to be considered as a school for the judgment.

Active Methods.—M. Maneuvrier, a writer on secondary instruction, in his recent book *l'Éducation de la bourgeoisie*,[1] has used the popular expression, "active methods," to designate those processes of education which address themselves directly to the mind, which seek first of all to develop the judgment, which, instead of loading and crushing the child's memory simply under the weight of endless didactic lessons, appeal to his individual activity, to his personal initiative.

The bad methods are the *passive methods*, that is, those that make machines, as Girard expresses it, "word machines, writing machines, reciting machines." They are employed by those who talk continually, who forget themselves in long expositions, who never allow the pupil to speak, so that the teacher does everything, the pupil nothing. "I would not," said Montaigne, "have the teacher alone think and speak; I would have him hear his pupil speak in turn."

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[1] *Éducation de la bourgeoisie sous la République*, Paris, 1888.

The good methods, on the contrary, the active methods, secure the constant intervention of the pupil ; they exercise him in judging, in thinking, and in expressing his thoughts. They accustom him, not only to find for himself a part of what he is to learn, and, after we have started him on the way, to discover bits of truth; but they accustom him also to speak, to think aloud.

"The true methods," says Maneuvrier, "are those which secure an almost equal intensity of thought in pupil and teacher. Let the teacher begin by setting forth the results of the science; let him make his instruction attractive by a short, substantial, well-prepared lesson. . . . . Nothing better. But that is not sufficient. The child must, as we say, put his own hand to the plow. Yes! the child should work; should speak, and write; should judge and criticise, should praise and blame, should experiment and reason; he should try his hand at all this under the eye and under the direction of an expert and devoted teacher. Such is the fruitful apprenticeship which will serve him always and everywhere."

The Judgment and the Different Parts of the Programme. There, are, properly speaking, no special lessons in judgment. The education of this master faculty of the mind should result from every department of instruction.

Girard has pointed out this result in the study of language. For the grammar of words he would substitute the grammar of ideas, that is, oblige the child to discover for himself the rules of syntax, to reason on the expressions which he employs and on the forms which he applies. "Thus the study of language," says Gréard, "was for him only an instrument by the aid of which, while teaching the pupil what is indispensable for him to know, he sought to exercise his judgment."

The study of number lends itself even more than the

study of grammar to the exercise of the judgment and the reason. "It is on the practice of calculation," says Gréard, "that Pestalozzi established his pedagogical doctrine," which had for its essential end to give to the child's mind "freedom of activity, self-command and accuracy." It is to be remarked, however, that calculation develops the reason proper, rather than the practical judgment. The demonstrations of arithmetic present an exactness, a severity, and also an abstract simplicity, which are by no means allowed in the delicate, complex and intricate questions of real life. But let us not imagine for all that that the habits of order and of method contracted in the study of the mathematical sciences have an indifferent value in preparing us even for practical judgment. It is to be noted, moreover, that instruction in number, while it is in itself a training for the reason, presenting as it does a systematically connected series of judgments and ideas, may become also an exercise in practical applications, if the teacher knows how to make an apt selection of problems taken from real life.

History has always been considered as the study best suited to form the judgment. For this purpose, we must show the child, not a simple succession or juxtaposition of facts, but a chain of causes and effects. He must be exercised, not merely in repeating from memory what has been related to him, but in discerning for himself the causes of events, in judging the men of whom he has been told, of appreciating their actions.

Imitation and Judgment.—In a word, it is by applying everywhere an active method, that the instructor will make of his pupils, not automatons who repeat mechanically the lesson learned, but living minds, capable, according to the extent of their knowledge, of pronouncing accurate and decided judgments.

"Many of the things which are learned on the benches of the class room," says Gréard, "are sooner or later effaced from the memory. But that which remains from well-directed studies, that which should remain from a primary education when a culture of the morals has been added to the intellectual culture which trains the mind, is a sound and enlightened judgment."

Let us not forget, however, that even in the education of the judgment and of the reason, there is a part to be played by imitation, by mechanical repetition, by the virtue of example. It is not merely by an incessant appeal to the intelligence of the pupil, by pressing questions, by offering him occasions for exercising his analytical faculty and his power of reflection, that the teacher will develop his judgment It will consist also in proposing to him only good models, in giving in himself the example of a judgment always correct, always reflective. In this atmosphere of good sense and reason, the child, through an instinctive imitation, will contract, in his turn, the habit of reflection and prudence. The qualities which characterize the instruction of the teacher will be quietly transmitted, by a sort of insensible contagion, to the mind of the pupil. And this is why an English educator could say: "The science of education consists in supplying the mind with facts in the order which best trains the reason."

Education of the Reason.—All that we have just said is applicable in part to the education of the reason, the reason being, under different forms, but the series of intellectual operations which lead up to and end in the judgment. Reason, without doubt, in its highest and most exact form, deserves special study: this will be the aim of the following lesson. But before becoming the essential spring of method, before being the principal instrument of scientific research,

the reason already intervenes in the simplest operations of the infantile judgment. In truth, judgment and reason are but different degrees of intellectual activity and of personal thought; and as Gréard expresses it in a page which deserves being quoted, and which summarizes the whole of this lesson, the purpose of education is to put this activity into movement, to excite it little by little by easy elementary exercises. The higher qualities of the reason will then appear spontaneously.

"If the reason of the child is still frail, with what accuracy it follows the hand that knows how to conduct it with skill!

"The best teacher is he who knows how to put this activity into movement. When the child has once made a start, it is sufficient to stimulate him gently, and to call him back when he goes astray, while always leaving to him, as far as possible, the toil and the satisfaction of discovering whatever we wish him to find. Let him form the habit of justifying whatever he asserts, and of expressing himself freely in his own language; allow him even to expose himself to error and have him correct it by showing him wherein he has failed in reflection; this will be the most profitable of lessons. When, from the beginning to the end of his studies, he shall have been subjected to this discipline, we may be assured of having formed a good mind, capable, whatever be the profession which he chooses, of a rational and successful application." [1]

SUMMARY.

64. The perceptions of the senses and of the consciousness, preserved by the memory, are, as it were, the materials of the mind; but the characteristic activity of the mind manifests itself in the judgment and the reason.

65. Since Montaigne, all educators are agreed in rec-

[1] M. Gréard, *Éducation et Instruction;* Primary Instruction, p. 91.

ognizing that the culture of the judgment is the crowning work of intellectual education.

66. The judgment, considered as the master faculty of the mind, is less a distinct operation than an aggregate of qualities, an intellectual habit; it is the synonym of accuracy of mind; it consists in discerning, in all things, the true from the false.

67. The exercise of the judgment, thus understood, supposes the intervention of general or abstract ideas.

68. In order that the child may deal surely and easily with general ideas and abstract terms, two rules must be followed: 1, never let an abstract term pass without explaining it to the child, at first by concrete examples, later by definitions; 2, accustom the child, by presenting to him a series of objects of like nature, to grasp their relations and resemblances, and to discover for himself the general idea.

69. Once in possession of abstract and general ideas, the child is capable of judging and reasoning; and the second step in the education of the judgment consists: 1, in exciting the initiative and the liberty of individual judgment; 2, in assuring its soundness and accuracy.

70. The liberty and the initiative of the judgment may be stimulated by multiplying interrogations, by soliciting the child's reflection, and by refraining from pointing out to him in an unkind spirit the errors which he may have committed.

71. Soundness of judgment may be assured by preventing the two principal causes of our errors: ignorance and precipitation or irreflection.

72. Instruction may be a discipline for the judgment only on condition that the teacher employ active methods, or those which address themselves directly to the mind.

73. Every subject of instruction, grammar, arithmetic,

history, etc., should afford the teacher an occasion for exercising the judgment.

74. Imitation, or the influence of example, also plays a part, but a secondary part, in the education of the judgment; the qualities of systematic instruction are transmitted by a sort of contagion to the mind of the pupil.

75. The culture of the judgment is confounded with that of the reason, the reason intervening in the simplest operations of intellectual activity.

CHAPTER VII.

METHOD.—ITS DIFFERENT PROCESSES.—INDUCTION AND DEDUCTION.

Method in General.—Method, in its general sense, is the order and continuity which we introduce into our thoughts and acts. It supposes the clear conception of an end to be pursued, and the organization of means for its sure attainment. From this point of view, method enters into every reflective undertaking, into all deliberate conduct. Nothing is well done without method, whether a military expedition, an industrial enterprise, or a voyage of exploration.

Thus understood, education also has need of method. It will be methodical if the teacher leaves nothing to chance, does not count on the good fortune of improvised effort, prepares his lessons in advance, calculates the employment of his time, regulates his work and that of his pupils according to a regularly prescribed programme; in a word, if he conducts all his school work with reflection and order.

Particular Methods.—But to follow some order simply is not sufficient: there is for each category of enterprises a special order adapted to the nature of the work to be done. There is, for example, the scientific method, which has for its end the investigation of truth, and there is the pedagogical method, the end of which is to communicate truth.

In this sense, there are then many distinct methods; and each particular method is a body or a system of rational pro-

cesses and coördinate operations, which experience and reason sanction as the best possible for the attainment of a given end.

Importance of Method.—No one questions the utility of method: to do so would be boldly to avow a preference for irreflection, heedlessness, and disorder, to prudence and sagacity. The absence of method condemns to impotence the most brilliant minds; it renders sterile the most laborious efforts. With method, on the contrary, even mediocre minds attain the end; they attain it with less difficulty than disorderly and heedless intelligences which lose themselves in their marches and counter-marches. To use Bacon's expression: *Claudus in via antecedit cursorem extra viam*, "the lame man who follows the good road outstrips the fast runner who departs from it."

But what is not so universally recognized is the utility of the study of methods. What good, says one, is to be derived from studying in books the learned methods which theorists have analyzed in minutest details? Is not the true method that which each one derives for himself from his personal reflections and his own experience?

Certainly one does not learn method in a manual of logic or pedagogy, as he learns the multiplication table in an arithmetic. We do not find a ready-made method in the writings of logicians, as we might find a rule in a box of instruments for use on paper. The most perfect method is worthless if we do not know how to use it. The value of the most perfect instruments depends on the deftness of the hand that uses them.

"The best tool," as M. Marion justly remarks, "is that which one selects for his hand and for which his hand is made."

But all these considerations do not tend to demonstrate the inutility of methods: they prove simply that it is necessary to appropriate, to assimilate, by fruitful reflection, and intelligent application, the methods whose theoretical rules are studied in books. These methods must become living, they must not be simply processes mechanically employed, and utilized without a consideration of their value. They must be the very spirit of him who applies them.

No doubt should be thrown on the value of processes which have been sanctioned by the experience of ages; so that even a man endowed with ingenuity, if he should desire to construct his own method, would do scarcely more than rediscover with effort what others have practiced before him, and fall back into the beaten paths. Would it not be better for him to acquaint himself at once with the road, through those who have walked there before him?

It does not follow from this that methods are regulations unalterable and fixed once for all. There is certainly much to be expected yet of future progress. As Madame Necker de Saussure has said, "Methods should be in a state of perpetual improvement." The essential part, however, is already established, and it is this essential basis that it concerns us to study, leaving the rest to the free inspiration of innovators.

Scientific Method.—It is logic that studies the rules of the scientific method. In this sense, method is a body of processes to be followed in the investigation and discovery of truth. Thus understood, according to the most competent logicians, method comprises four parts: observation, generalization or definition, induction, and deduction.[1]

[1] See, for example, *Inductive and Deductive Logic.*—Bain.

The first operation is restricted to facts, the other three to the generalization of facts.

The starting point of all science is evidently observation, the knowledge of particular facts. If it concerns the external world, observation supposes the exercise of the senses; if it concerns the internal world, the mind, the thinking subject, observation supposes the exercise of consciousness. Observation, to be exact and complete, admits, moreover, certain rules which vary with the nature of the objects observed.

The second step in method is definition. By comparing, classifying, and assimilating, according to one or more common qualities, a certain number of particular objects previously observed, the mind arrives at a general idea the meaning of which is expressed by the definition which may be given it. This second operation supposes several successive stages: comparison, classification, abstraction, and the use of general terms; but all these operations which are involved in generalization may be summarized in the definition. We do not have, in fact, a general notion save on condition of being able to define it. All systems of logic have precise rules for definition.

Induction is also a generalizing process, but it differs from the intellectual movement which ends in definition, in that it conducts the mind, not to a simple notion, but to a proposition. A general idea, as iron, magnetic property, is one thing; a proposition, a judgment, an inductive truth, as, iron may acquire magnetic properties, is another. General ideas are valuable, moreover, only as they may enter as elements into inductive propositions.

When induction has done its work, it remains to apply the truths which it has established to new cases. This is the special office of deduction, which, taking for a starting point a general proposition and comparing it with other

general propositions or with some particular facts, derives therefrom new propositions. For example, induction teaches us that iron is a magnetic substance; now, we know that within the earth are masses of iron; whence this conclusion, that the existence of these masses of iron in the interior of the earth is the cause, or at least one of the causes, of terrestrial magnetism.

It is to establish with precision the conditions of the inductive and deductive processes, these two forms of reasoning, that logic devotes the major part of its efforts.

Method in Pedagogy. — Now, laying logic aside, let us return to pedagogy, and we shall be convinced that, for the communication of truth, education has at its command scarcely any other means than those which the scientist employs for the discovery of truth.

It is even to be observed that method in pedagogy has followed, step by step, in their evolutions and transformations, the changes introduced by the progress of the centuries into the scientific method. As long as deduction remained the sovereign mistress of logic, formalism, the abuse of abstractions, and the predominance of general rules and formulas, were the supreme law of pedagogy. It was only when logic reformed its method, when Bacon dethroned deduction and the syllogism to enthrone experience and induction, that, by an almost immediate consequence, education also began to recommend induction, observation, and inductive processes. Comenius has been justly called the Bacon of pedagogy, because he, so to speak, simply applied to education the principles of the *Novum Organum.*[1]

[1] See our *History of Pedagogy*, p. 123.

Methods of Instruction.—The pedagogical method, then, is, in truth, merely the application to instruction of the rules of the scientific method.

For organizing knowledge in the mind of the child, there are rules analogous to those which the scientist applies in constructing science itself.

Moreover, the method of instruction will vary, (1) with the nature of the object to be taught: grammar and arithmetic, for example, will not be taught by the same method; (2) with the age of the pupil: we will not teach history to the pupils of a primary grade by the same methods that we employ in teaching pupils in the higher grade; (3) and, also, with the different grades of instruction: in the normal school a study will not be pursued in the same way as in the primary school.

In other words, the method of instruction should always conform and adapt itself to these three general rules: (1) the nature or particular character of the knowledge to be imparted to the child; (2) the laws of the progressive evolution of mind, at the different periods of scholastic age; (3) the peculiar end and scope of each grade of instruction.

Let us add, also, that the best method of instruction is recognized in this: that it facilitates the work of the pupil, not that of the master. It is not a question of putting into the teacher's hands short methods, mechanical instruments which relieve him of activity and effort; but of having him employ the processes best adapted to the nature and wants of the pupil.

"The teacher is always involuntarily inclined to choose the process of instruction which is most convenient for himself. The more convenient this process is to the teacher, the more incon-

venient it is to the pupil. That alone is good which satisfies the pupil."[1]

Methodology.—Although we do not like the word, it must be pronounced; methodology is the term which is used, especially abroad, to designate that part of pedagogy which treats of methods of instruction. It is thus defined by the latest treatise on pedagogy which has appeared in Belgium:

"Methodology is the science of instruction. It sets forth the principles, rules, and processes which constitute method. It comprises general methodology and special methodology; the one treats of points which concern all branches of study; the other is occupied with each branch in particular."

Methods, Modes and Processes.—We have noted elsewhere[2] with what strange prolixity foreign educators, in the study of methods, multiply distinctions, divisions and subdivisions, so as to enumerate, in an empty verbiage, a multitude of forms, processes or methods, each of which has its definition and its laws.

Much is to be gained in avoiding this new scholasticism and this verbal formalism. Without multiplying distinctions, it is sufficient to distinguish methods, forms, modes and processes.

Methods, which are of first importance, correspond to the order followed in studies: they reduce themselves to two, which may be called inductive and deductive, according as induction or deduction predominates.

But there is something more than the internal order of the truths which the teacher sets forth or suggests, something more than the inductive or deductive course of instruction.

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[1] Tolstoï, *L'École de Yasnaia Poliana*, p. 98.

[2] See Compayré's *Lectures on Pedagogy*.

There is also an external form which is given to instruction; the teacher either does all the talking himself as he sets forth what he wishes to have learned, or he takes turns with his pupils, as he interrogates them and provokes their replies. Hence two forms of instruction: the expositive or didactic form; the interrogative or Socratic form.

We must recall also the old distinction of *modes* of instruction, individual, simultaneous, and mutual, according as the teacher addresses himself to an individual pupil, or to a whole class, or again, withholding his aid, as he leaves the pupils to instruct one another. The simultaneous mode is evidently the only one which, as a general rule, is adapted to public instruction. But it is not necessary, however, to proscribe absolutely the accidental and exceptional use of the two other systems. The teacher should be able, in his expositions, while addressing all to address each one individually, and to find, when explanation is necessary, details which are more particularly adapted to the aptitudes and tastes of this or that pupil. Interrogations, moreover, are always individual. On the other hand, in classes which are too large, but are still entrusted to the direction of a single teacher, it may be useful to resort sometimes to mutual instruction.

Finally, let us note the distinction between methods and processes. Methods fix the general principles which preside over instruction, which regulate the order and sequence of studies; processes are the particular means which are employed in the application of methods. For example, to demonstrate geometrical truths is a method, a deductive method; to explain them on a black-board and have them in turn repeated by the pupils, is a process.

Observation and Definition.—It is with methods that we are chiefly concerned in this place. As we have said, peda-

gogical methods are, so to speak, nothing more than scientific methods applied to instruction. We shall find in them, therefore, the four successive processes which logic distinguishes in the method of the sciences; and first, observation and definition.

Observation, or in other terms, intuition, is the necessary beginning of all instruction as of all science. Certain educators have wished to make intuition a special method complete in itself. This is as absurd as if one should wish, in the sciences, to reduce everything to the simple observation of facts. The truth is, that intuition is a part of method, one of the essential elements of all instruction truly rational and adapted to the aptitudes of the child. One could not multiply too much, especially in the beginning of instruction, the direct perceptions which insure a clear and vivid intuition of objects.

But these particular observations are only a point of departure, a preparation. They would be of no service of themselves if they were not the elements of generalization, of that intellectual activity which enables the mind to discern in the diversity of individual things, common points, resemblances and relations, and thereby to conceive general notions which find their formula in well framed definitions.

It is a difficult art, that of definition, in pedagogy as in the sciences. According to the rules of logic, definitions should be clear, they should employ words that are already familiar or intelligible to the pupil; they should be exact and complete.

Let us distrust those verbal definitions which teach nothing, which are mere tautologies, and which Belgian educators do not sufficiently avoid when they say, for example, that "judgment is the faculty of judging, reason is the faculty of reasoning." The definition, to be anything more

than useless verbiage, should determine the essential elements of the idea defined: for example, judgment is the act of affirming the relation of two ideas; reason, the act of affirming the relation of two judgments.

Induction and Deduction.—Observation bears only on particular facts, and definition on general ideas. The human mind would be very much limited if it could not go beyond facts and ideas. It is through reason that it extends its domain, and that, profiting either by its first intuitions or the general notions derived from them, it is able, either inductively or deductively, to handle these elementary data, and to arrive, not merely at ideas, but at general truths.

From this point of view, that of the logical order of truths, there are only two methods of imparting knowledge, as there are only two methods of acquiring it: induction and deduction. Sometimes the teacher takes for a starting point facts observed in intuition and generalized into definition; and leading the pupil into the work of his own thought, he rises to the law which governs these facts,—this is the pedagogical application of the inductive method. Again, he takes as his basis general truths; these general truths being either rational principles or inductive propositions; and by deduction he passes from these principles, rules, and general laws, to applications, to the particular cases which naturally flow from them. The method then becomes deductive.

Let us take examples. In teaching grammar, if we first explain the rule and then seek its applications, the process is deductive; on the contrary, if we first present to the child examples, or particular cases, in order to suggest to him the idea of the rule, the process is inductive. The teacher of geometry who at the outset lays down axioms and defini

tions, and proves that such or such a theorem is their necessary consequence, makes a demonstration, or, what amounts to the same thing, a series of deductions. The teacher of physics who appeals to the observation of his pupils, experiments before them, shows them the objects to be studied, analyzes their elements and infers from them a general law, employs successively the different processes of induction. In history also, we proceed by deduction or induction according as we take for our starting point the definition of feudalism, for example, or the different facts which constitute feudalism.

Inductive and Deductive Method.—In fact, in every department of instruction, both induction and deduction are employed in turn.

Thus, even in arithmetic and geometry, it is a good method to resort at first to inductive processes, experimental calculation, or to sensible observations of geometrical forms. Just so in the physical sciences deduction also plays a part; as, when a general law has been inductively established, we deduce its consequences.

It is nevertheless true that induction predominates in the so-called sciences of observation, physics, and the natural sciences; deduction, on the contrary, in the abstract or exact sciences.

As logicians often distinguish these sciences by calling the first the inductive sciences, and the others the deductive sciences, so in pedagogy we call that the inductive method which most often appeals to induction; and that the deductive method in which the principal part pertains to deduction.

Analysis and Synthesis.—When we have distinguished in the method of instruction the inductive and deductive methods, everything on this point has been said; and it is

altogether useless after this to resort to other fine terms, too much favored in certain schools of pedagogy, as, for example, analysis and synthesis.

There would be, according to certain educators, an analytical method and a synthetical method. The best proof that the words analysis and synthesis should be banished from pedagogy, is the fact that authors are not agreed as to what these terms should mean; some call synthetic what others call analytic, and *vice versa*. Thus, Horner, a Swiss educator, asserts that "the synonym of demonstration is deduction and analysis; that the inventive process is often confounded with induction and synthesis." Quite to the contrary, a French educator, M. Charbonneau, whose work has for a long time been considered classic, affirms, and general usage sustains the affirmation, that the demonstrative method is also called synthetic, while invention or induction is called analytic.

In truth, analysis is at once an inductive and deductive process. In the first place, analysis consists in separating the elements of a concrete substance; as, for example, when we decompose water. In this case analysis is directly connected with experimental and inductive processes. But there is also an abstract analysis, purely mental, which consists in distinguishing the different elements of a general idea. In this case analysis is a particular aspect or phase of the deductive method.

We shall not speak of synthesis, the meaning of which is still more complicated and confused. We shall conclude that there are, at bottom, but two essential methods, induction and deduction.

The Method of Descartes.—We are far from having studied all the questions involved in the problem of method. We

should remember, first of all, that, as Descartes says, the principal thing is not in possessing a good mind, but in applying it well. In one sense, a bad method, or any procedure whatever, is better than no method at all.

"Those who walk very slowly," says the author of the *Discours de la Méthode*, "may make better progress if they always follow the right road, than those who run, but depart from it;" and, although the rules of Descartes were established exclusively in view of scientific research, pedagogy may derive profit from them. These rules, as we know, are four in number, and are summarized as follows:

(1) Accept as true only what is evident, carefully avoiding haste and bias in our judgments; (2) divide difficulties in order the better to solve them, which is equivalent to saying, use analysis; (3) conduct your thoughts with order, beginning with objects the simplest and most easily understood, in order to arrive, little by little, as by steps, at the most complex and most difficult knowledge, a process which tends to place intuitions or particular observations before abstract and general rules; (4) finally, make complete enumerations, so as to omit nothing.

SUMMARY.

76. Method, in general, is the order and the arrangement which we introduce voluntarily into our thoughts and our actions; it supposes a clearly conceived end, and carefully calculated means.

77. There are as many methods as there are human enterprises and efforts. Particular methods are a body of rules and rational processes adapted to a given end.

78. To say that method is useful and necessary, is to say simply that we prefer order and reflection to irreflection and carelessness.

79. It is worth our while to study the methods sanctioned by experience, for to follow them we must know them.

80. But the study of methods is useful only on the condition that they are appropriated and made our own by reflection and use.

81. The scientific method studied by logic comprises four successive processes: Observation, definition, or generalization, induction and deduction.

82. The pedagogical method is scarcely more than the application to instruction of the rules of the scientific method. So long as the reign of deduction and the syllogism lasted in the sciences, formal, mechanical and deductive methods prevailed in pedagogy.

83. The method of instruction should vary with the nature of the knowledge, with the age of the pupil, with the purpose of each grade of instruction; it should be accommodated to the pupil rather than to the teacher.

84. Methodology is the term applied to the science of the methods of instruction. There is a general methodology and a particular methodology.

85. General methodology treats of the essential methods which are employed in all parts of instruction. The methods which regulate the logical order of the truths imparted differ, moreover, from the *forms* of instruction, which are expositive or interrogative, from the *modes*, which are simultaneous, individual or mutual, and finally, from *processes*, which are but the detailed application of general methods.

86. The pedagogical methods suppose four distinct processes: first, the observation or intuition of particular facts; second, the generalization of the ideas which the definition formulates and explains.

87. The two other processes of method are induction and deduction; induction, which rises from facts observed

or generalized to general truths and laws; deduction, which descends from rules, laws and principles to particular cases.

88. Induction and deduction play a part in all parts of instruction, but induction predominates in the study of the physical and natural sciences; deduction, in the study of the abstract sciences.

89. Method is said to be inductive or deductive according as it employs more frequently induction or deduction.

90. Analysis is simply one of the elements, either of the inductive method or of the deductive method.

CHAPTER VIII.

METHODS OF INSTRUCTION—SPECIAL STUDY OF THE PROCESSES APPLICABLE TO EACH SUBJECT IN THE COURSE.

Methods of Instruction.—There are two ways of studying methods of instruction and what are called "the processes applicable to each subject in the course."

We may take up the different subjects in the course, one after another, and inquire how they ought to be taught, devoting special chapters to reading, writing, grammar, history, ethics, etc. This is the plan followed in our *Lectures on Pedagogy*,[1] and we shall not repeat what is there said.

Or we may examine the differences which result from the peculiarities inherent in each study, and then generalize, or examine *in abstracto*, the methods that are employed in all the subjects of the course. This is the plan which we shall follow in this treatise. Whatever, in fact, may be the nature of the object studied, we must always return to some one of the elementary processes which are modified doubtless in accordance with the differences in the subject matter to be transmitted, but which, in reality, are always the same: sense-intuition, mechanical exercises, the recitation, the study of books, the didactic lesson, interrogation, themes, exercises in composition, personal invention.

[1] *Lectures on Pedagogy*, D. C. Heath & Co., Boston.

Here we have, so to speak, the *methodic elements* of all instruction, which we shall examine one after another.

General Principles.—Belgian educators pursue another course; they enumerate in never-ending lists, the fundamental principles of a good method. For example, here is the catalogue drawn up by M. Aubert, director of the Normal School of Mons. He first distinguishes six categories of principles according as they have particular reference: 1, to the teacher; 2, to pupils; 3, to both teacher and pupils; 4, to the subject-matter of the lesson; 5, to the exposition of the lesson; 6, to the sequence of studies. Each one of these categories would itself comprise different principles, such as (1) the necessity of the teacher's vocation and of his preparation for it; (2) the necessity of attention, of the real exercise of the intelligence, of the active co-operation of the pupil, and his need of personal effort; (3) the necessity of moderation in the work required, of a just distribution of the teacher's efforts among all his pupils, of a correct classification of pupils, of a judicious assignment of place to each pupil; (4) the necessity of subject-matter which is both useful and attractive; (5) the necessity of intuition and animation; (6) the necessity of a wise co-ordination of studies, the necessity of studies by concentric courses, the necessity of a slow and progressive course,—in all, seventeen principles, no one of which, surely, is unworthy of arresting a moment's attention.

However, it is easy to reduce this long list, and to condense into a few essential rules the principles which should guide the instructor.

First, it is quite useless to speak of the teacher's call, for we address ourselves only to competent instructors, and we have no advice to give to those who do not possess the

qualities necessary for the work of teaching. On the other hand there is no occasion to examine the utility of the subjects taught; it is the programme which determines these, and in its construction it is evidently inspired by considerations of utility. The place to which pupils should be assigned, and their classification, are not principles of teaching, but at most only rules for the material organization of classes. So also the distribution of studies by concentric courses is but a process which may be applied to most branches of instruction,—to history, for example. Attention, the real exercise of the intelligence, the active coöperation of the pupil and his personal efforts, these really constitute but a single principle,—that which requires the pupil to participate in the work of the class, and forbids the teacher to act alone in the presence of inert and passive auditors. We see, then, without stopping to dwell on the matter, that the analysis made by Belgian educators is defective, either because it multiplies subtle distinctions too much, or because it connects with instruction material processes which have no direct bearing on instruction itself.

We may then restrict ourselves to the analysis which we have previously given, and which comprehends all the elements essential to methods of instruction.

Respective Functions of Teacher and Pupil.—In all instruction there is certainly a part for the pupil and a part for the teacher. But, however necessary it may be to give greater and greater extension to the rôle of the pupil for the purpose of calling into play his intellectual activity—which is the grand purpose—the teacher's part is always preponderant. Even when he does not intervene directly by verbal explanations or formal lessons, it is he who

controls the pupil's work, who chooses the material objects to be observed and the texts to be recited; who traces on the board in the presence of his pupils the copies to be written; and who, finally, is in all things the pupil's guide and inspiration.

But, on the other hand, the pupil ought never to remain inactive. Even when the teacher is speaking, and seems alone to be active, for example, in a somewhat extended exposition, the pupil intervenes and takes part in the master's work by his constant attention, by the notes which he takes, and by his effort to follow and comprehend the lesson which he hears.

Instruction can be profitable only on the condition of being a process in which teacher and pupil incessantly coöperate, where the action of the teacher is of no avail unless it excites the corresponding activity of the pupil. "Stimulate self-activity," it has been justly said, "is the grand precept of instruction." It might well be called the unique precept; for it contains in germ all the others.

Intuition.—There was a time when methods of instruction and study consisted merely in dictation by the teacher, and in learning by heart by the pupil. The appearance of the book was a step in advance; for the book, although capable of misuse, if we seek in it nothing but words and an exercise of verbal memory,—the book explained in class or read attentively by the pupil, is an excellent instrument of reflection, personal criticism and fruitful meditation. But modern pedagogy has found something besides the book; it has placed the mind of the child, without intermedium, face to face with real objects; in the immediate and direct intuition of things, it has undertaken to find the starting point of all intellectual culture. The book is

merely the thought of another; and the oral lesson of the teacher is also the thought of another; but intuition is the personal thought of the pupil, excited and provoked by the sight and handling of objects to be known and studied.

Intuition, then, is one of the essential elements of every method of instruction. It is the best introduction to the study of language; for it is no longer admissible to teach words to the child, at least in the first years of life, without presenting to him the things which these words designate. And even at the age when the pupil is well nigh in possession of his mother tongue, intuition ought still to intervene, in order to assist in the acquisition of scientific knowledge and to facilitate the study of history and geography. There is hardly any part of the programme where we cannot usefully employ intuitive processes.

"Do not tell your pupils that the gilly-flower has four petals and five stamens, without making them examine it. Do not tell them that sorrel is sour, without making them taste its leaf. Do not speak to them of the composition of the air, without preparing in their presence oxygen, nitrogen and carbonic acid. Do not describe the costume of the ancient Belgians, without a picture which represents it. Teach geography with globes, maps and engravings. Speak of the virtues and defects of character in connection with the conduct of children, and with narratives reciting facts which they can comprehend." [1]

Intuition, moreover, does not consist merely in causing natural objects to pass before the eyes of the child; but in order to organize sense instruction it may resort to artificial means, to diagrams, to illustrations, and to pictures.

School Apparatus.—If instruction were but an intellectual commerce between the mind of the teacher and the mind

[1] J. Aubert, *op. cit.*, p. 170.

of the pupil, it would suffice for the equipment of the learner and the completeness of the school outfit that the pupil have in his hands the material for writing and taking notes. But the oral lesson of the teacher is not all. It must have the aid of material instruments, and must put in operation, so to speak, certain school implements, all of which tend to the same end, and are the auxiliaries of intuition. Of this number are the blackboard and the numeral frame.

The Blackboard.—Heretofore the best schools were those which consumed the most ink and paper. To-day the best schools are those where teachers and pupils use the most chalk and most often resort to the use of the blackboard. In American school-rooms the entire wall is transformed into a vast blackboard, where several pupils can work at the same time. At the very least, it is necessary that there should be a blackboard in every school-room, in plain sight, on which the teacher translates his lessons in a way that appeals to the eye, not only in the teaching of number, but in reading, writing, grammar—in a word, in almost all the studies of the course.

In one of his memoirs, M. Gréard recalls the fact that in the year 1800, in a report addressed to the prefect of the Seine, Citizen Zolver mentioned as a wonder the blackboard which he had found in a certain school. So, also, as late as the year 1867, wall maps were found only in schools of the higher grade:

"Just as though," adds M. Gréard, "indispensable in all grades, these aids were not more particularly useful in the classes where, in order to incite the intelligence of the child, it is necessary to begin by appealing to his eyes! In subjects which admit of description, every lesson which can terminate in a palpable demonstration, and which is not brought to that point, is incom-

plete and insufficient. In the more abstract subjects, such as number, spelling and history, the board which, under the living voice of the teacher, rallies every eye, and summons, sustains and excites the attention, becomes the surest stimulus, both to individual effort and to the collective activity." [1]

The Numeral Frame.—In the study of arithmetic, at least at the outset, intuitive processes may be of great assistance, as when we present to the eyes of the pupil points and lines drawn on the blackboard, or when we put in the child's hands real objects, or, finally, when we make use of artificial aids like numeral frames which are used in infant schools for introducing little children to the first use of numbers. But of course intuitive calculation is but a preparation for mental calculation, and concrete intuition ought as soon as possible to give place to abstract reasoning.

Pictures and Maps.—Pictures are coming more and more to play an important part in instruction; they constitute, so to speak, an intuition of the second degree. Especially in history, nothing is more useful and interesting than pictures which represent celebrated men, monuments, and events of great importance.

In geography it is not possible to do without wall maps, or at least without an atlas; while for initiating the pupil into the primary elements of geography, we may resort to the direct intuition of varieties of surface and structure of soil.

"It is through the eyes that geography should be taught," says an authority on this subject. "To use an American phrase, the lesson in geography should be a lesson on places which would be neither less useful nor less interesting than a lesson on things."

[1] M. Gréard, *Éducation et Instruction*, p. 79.

Intuition in the Teaching of Physical Science.—In the domain of the natural sciences there are a thousand occasions for the application of intuitive processes. And in truth, in the primary school, the teaching of the physical and natural sciences ought to be almost exclusively a series of experiments. At first these experiments will be those of the laboratory, those which will require the use of physical apparatus; but appeal must also be made to less costly and less difficult experiments which nature produces every day before our very eyes: a tub of water found burst in the morning through the effect of frost; a window which closed freely yesterday but which sticks to-day in consequence of moisture; a brook which in its course bends a willow twig planted in its bed; the air (wind) weighing down the stalks of wheat or the tops of tall trees; the resistance offered by water to a stick which is moved about in it, etc.

We are far from having enumerated all the accessory processes connected with intuition. Collections of geometrical solids, the outfit of the metric system, school museums, and botanical gardens, are also the indispensable auxiliaries of object lessons and the intuitive method.

General Rules of Intuition.—The great importance of direct and indirect intuition in instruction cannot be denied; but yet we must be on our guard against making an abuse of this new method which is profitable only as we know how to use it with discretion and precaution. We know children who, having seen much, have doubtless retained much, but whose mind has been wearied and the imagination confused by presenting too many things to them. There may be excesses in intuition as there have been excesses in verbal recitation. Let us take care lest the mind of the child whom we burden with object lessons, and whose attention we

direct over thousands of images, escape from these exercises exhausted and overpowered by extreme lassitude, just as our imagination is when we have attempted to visit in a single day all the nooks and corners of a vast exposition.

Judicious and moderate, intuition ought also to be methodical and orderly. Object lessons would be only a chaos in which the mind would lose itself, if they were to go at random in the vast field which is open to them. Nothing is more useless, and, we may add, nothing more dangerous, than object lessons given without sequence and without order.

Let us not forget, moreover, that intuition, though it consists essentially in placing the child face to face with things and in leaving him, so to speak, alone in the presence of objects,—intuition is not actually separable from certain other processes of instruction. The teacher has his part in the process, not only through the choice which he makes in the objects to be placed in succession before the eyes of the child, but also through the explanations which he gives, not in the way of precise statement and didactic lesson, but by familiar conversation, by timely interruption, and also by the reflections which he provokes while questioning the pupil. In object lessons, says Herbert Spencer, it is especially the child who ought to speak; the teacher should encourage him to speak as much as possible on each object which he shows to him. But in order that the child speak, it is evident that the teacher must set him an example. Consequently intuition supposes, not only complete and well arranged collections, museums and instruments, but also a skillful teacher, accurate in his language and knowing how to associate with intuition the other processes of instruction.

Mechanical Exercises.—It is a vain wish to banish as much as possible from the school mechanical exercises, and demand that instruction shall be full of life and intelligent activity. Human nature does not tolerate a continuous tension of the active and reflective faculties. According to the profound saying of Pascal, "we are as much automatic as rational." And the great thinker added: "How few things are demonstrable! Custom makes juster and more creditable proofs; it is too much trouble to have the proofs of the truth always at hand; the automaton must be made to believe through custom."[1]

These maxims are applicable to instruction. Doubtless we should try to diffuse floods of light and intelligence over the work of the school; but do not let us flatter ourselves that we can seriously instruct the child without appealing to the automatic power of habit or custom and without resorting to mechanical exercises.

Reading and Writing. —There are, moreover, branches of instruction which necessarily suppose the prolonged repetition of certain mechanical acts in which the intelligence plays a lesser part than memory and habit. We do not purpose to return, in this place, to the different processes in use for teaching to read and write; but it is very evident that whatever effort we may make to facilitate the apprenticeship of the child, as by uniting writing with reading, or associating drawing with writing, we shall never succeed in suppressing in this part of instruction the element of mechanical routine which is necessarily involved in it. Here, more than anywhere else, the child must be constantly repeating the same operations, and, so to speak, must incessantly go and come over the same traces.

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[1] Pascal, *Pensées*, Edition Havet, p. 158.

Orthography and Dictation. — In the teaching of language we should doubtless employ exercises in reading, and in oral and written work, which at the same time allow the child to develop his intelligence; but yet it is not possible to dispense entirely with literal recitations and spelling exercises where memory and habit are of more account than judgment and reasoning.

The Recitation. — In all the subjects of the course, as we have said, there are things to be learned by heart; and although we must strictly follow the rule which requires that nothing shall be learned by heart save that which has been previously explained and understood, the literal recitation of it still remains in itself a purely mechanical exercise of the memory. A given text is learned only on the condition of repeating mechanically, many times, the words which compose it.

And yet, in instruction of all grades, there is no exercise more important than recitation. I do not speak merely of rules and formulas which are properly known only on condition of having retained them word for word; but I speak also of literary recitation which is too little practiced in our schools, but which is, nevertheless, the best means of correcting and purifying the language of pupils, at the same time that it furnishes the mind with beautiful sentiments and grand thoughts.

"Since children have been found reciting and reciting, — grammar, history, geography, etc., without comprehending, memory and books have been tabooed; everything must be learned by intuition, by the judgment and the reason. If I dared give to my thought an aphoristic form, I would say to all, great and small: Comprehend, and then retain by heart all that you can." [1]

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[1] E. Rendu, *Manuel de l'Enseignement Primaire.*

The Office of the Book.—If in modern instruction we recognize the necessity of making things speak before allowing the teacher to talk; and of surrounding the child with concrete realities, or at least with the pictures which, by appealing to the eye, provoke indirect intuitions, it is no less indispensable to maintain the method of instruction by books. The book remains the pupil's instrument *par excellence*, and we cannot applaud the prejudice which through reaction against a "livresque" education, goes so far as to proscribe, or at least to decry, the use of books. We must not forget that after all the purpose of primary instruction is to inspire children with a taste for reading. It would be a strange means of accomplishing this purpose to begin by suppressing all the books in the school.

But books are not merely the future instruments of personal education, and of that progressive instruction which is continued during life, instruments which we must be taught to use at an early hour, if we wish to form the habit of employing them usefully. Books are an invaluable aid to school instruction itself, and we see no way of doing without them if we wish to fix in the child's mind knowledge which is exact and durable. Besides the books of the school library, which will furnish entertaining or instructive reading that will give extension to the mind and open to it new horizons, there will also be text-books in the pupil's hands which, under different forms, such as manuals, outlines of history, elementary treatises on grammar, etc., will serve as guides and will give completeness and exactness to the oral instruction of the teacher. In the complex work of instruction there must neither be prejudice nor exclusive method. Everything should contribute to it,—the personal intuitions of the pupil, the expositions of the teacher, apparatus, and instruments; but also the

book, which, read with attention and with something of the critical spirit, is still the best instrument for intellectual emancipation and the development of knowledge.

SUMMARY.

91. We may discuss methods of teaching in two ways: we may either examine in succession, in their special processes, all the studies of the course; or we may distinguish and study one after another the essential processes applicable to all instruction.

92. These essential processes, which might be called the elements of methods, are as follows: intuition, mechanical exercises, the recitation, the study of books, the didactic lesson, interrogation, and lastly, the compositions of the pupil.

93. Belgian teachers have drawn up long lists of the fundamental processes of method. They distinguish, for example, the principles relative to the teacher, to pupils, to both teacher and pupils, to the topic of instruction, to the form of the lesson and to the succession of studies.

94. The general principle of all instruction is that there ought to be a constant coöperation between pupil and teacher; the activity of the teacher is valuable only as it provokes the corresponding activity of the pupil.

95. Intuition is an essential element of every method of instruction; it substitutes for the study of words the direct presentation of things.

96. Intuitive processes do not consist merely in exhibiting such objects as nature presents; but they resort to apparatus and to instruments which facilitate intuition.

97. School apparatus plays an important part in modern instruction. It comprises the black-board, which should be used in every subject of instruction, and also

certain devices adapted to the teaching of certain subjects of the course, such as the numeral frame, pictures, maps, physical apparatus, botanical gardens, etc.

98. Intuitive instruction ought to be temperate, discreet, methodical, and orderly; it implies, moreover, a constant intervention of the teacher, who by his explanations and questions excites and guides the intelligence of the pupil.

99. Instruction should not require a constant action of the intelligence and reflection. It supposes mechanical exercises, the child being "automatic as well as intelligent;" especially while learning to read and write, and also in exercises in orthography and dictation.

100. The recitation is also a mechanical exercise; we must learn by heart as much as possible, but on condition of having thoroughly understood it previously.

101. Books play an important part in instruction, either as instruments devised for completing and fixing the oral instruction of the teacher, or as entertaining and instructive reading lessons which extend the pupil's knowledge and liberalize his mind.

entangle the tens of thousands of these parallel lines seen in the spectrum. But it has been definitely established experimentally that this multitude of lines may be divided up into groups, each group representing a chemical element, and every chemical element being represented by a group; also that each group includes a number of "series", the repeated series for each element being remarkably alike though found at different positions in the spectrum. That the disentanglement has been effected speaks volumes for the patient research that the work has involved.

All the lines are believed to represent *waves* of definite length and frequency. The wave-lengths are easily measured, and since the velocity of all the waves is the same, the frequency can be calculated ($v=n\lambda$). The measurement of X-rays may be made either by a glass reflection grating (Siegbahn's method), or by the X-ray spectrometer (the result of Laue's discovery of the use to which space-structures of crystals may be put), Bragg's method. Our present knowledge of electromagnetic radiation extends over the 70 octaves of wave-lengths from ·001 A.U. to 1000 km., but the visible spectrum extends over only the 1 octave of wave-lengths 3900 to 7600 A.U.[1] The best known "series" of lines for the group belonging to each element appears in this visible part of the spectrum, but the other series of each group in the infra-red and ultra-violet parts of the invisible spectrum are equally important. A few details of the hydrogen spectrum—the simplest—will help to elucidate what is to follow.

The best-known lines in the H-spectrum are the three discovered by Fraunhofer as black lines in the solar spectrum; the one in the red he labelled C; the one in the greenish-blue, F; the one in the indigo, G. We may call them B, C, and D respectively, and we know a fourth fairly prominent line E, as well as a number of fainter lines crowded together and finally coming to a limit in the form of a "fade-away", and termed Z.[2] Thus we think of the series as B, C, D, E, . . ., Z. The series itself is called the "L" series; it is the one series in the visible spectrum. There is a similar series (K) in the ultra-violet, and still others (M, N, O) in the infra-red. In each series the same letters (B, C, D, E, . . ., Z) are used to distinguish the spectral lines, though not all the lines appear in the various infra-red series.

[1] Wave-length is expressed in Ångström units (A.U.) $=10^{-8}$ cm. $=1/10$ $\mu\mu$. Spectral lines are represented by *wave numbers*, obtained by dividing 10^8 by wave-lengths.

[2] This B, C, . . ., Z notation is now seldom used, but it is useful and clear in our elementary exposition.

Hagenbach measured the wave-lengths of the 5 principal H-lines in the visible spectrum. The results were:

6563·04
4861·49
4340·66
4101·90
3970·25.

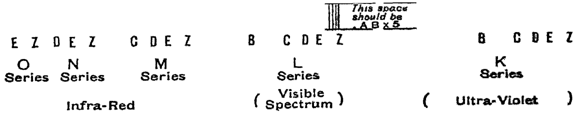
But he could not find the general term, or, indeed, any relation amongst the numbers. He handed over the problem to Balmer, an assistant master in a Basel secondary school, who discovered the general term to be

$$\lambda = \mathrm{B}\left(\frac{n^2}{n^2 - 2^2}\right),$$

where B is a constant, since called the Balmer constant, of the value 3645·6, and $n =$ the natural numbers 3, 4, 5, 6, 7.

If *frequencies* (reciprocals of lengths) had been considered, the analogous formula would have yielded the constant 109678, which is usually called the Rydberg constant and written R.

Here is a diagrammatic view of the successive Hydrogen series in the spectrum. The L series is in the visible spectrum.



The L series in the visible spectrum was the first discovered. When the other series were discovered, they all *seemed* similar to the L series. The wave-lengths were measured: did they square with the Balmer formula? These points should be noted:

1. The first (or K) series is far up in the ultra-violet.
2. The second or original Balmer (or L) series is in the visible spectrum.
3. The third, fourth, and fifth series (M, N, O) are in the infra-red.
4. The " head " of each series is a fade-away called Z.

5. The other end of each series is called the "fundamental". The fundamental of the K series is the line which we have called A; of the L series, B; of the M series, C; and so on.

6. The first and second series are a long way apart, about 5 times the length of the distance AB.

7. The K series less the A line gives the L series; the L series less the B line gives the M series; and so on.

8. The spacing between the lines (between C and D, for instance) seems to be the same for all.

Ritz tried a modified formula $\frac{1}{m^2} - \frac{1}{n^2}$, giving different values of m to the successive series (values of n as before). Writing it in the form $B\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$, he gave B the arbitrary value 900. This merely affects the scale, of course, and not the relative values.

Lines, and Values of n.	Series, and Values of m.					Interval Differences.
	K; 1.	L; 2.	M; 3.	N; 4.	O; 5.	
A; 2	108	0	—	—	—	
B; 3	128	20	0	—	—	20
C; 4	135	27	7	0	—	7
D; 5	138·24	30·24	10·24	3·24	0	3·24
E; 6	140	32	12	5	1·76	1·76
..	..	..	..	..	..	
..	..	..	..	..	..	
..	..	..	..	..	..	
Z; ∞	144	36	16	9	5·76	—

In the above table, note carefully:

1. The relatively large values of the frequencies in the K and L series, and the consequently relatively long distance apart of these series in the spectrum.

2. The intervals between the corresponding lines, shown in last column, are actually the same in all the series, as appearances led to believe.

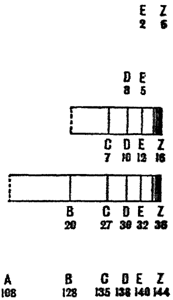
3. The intervals diminish as n increases.

4. The head (Z) of each series is the same distance from the corresponding lines.

5. The intervals in each series are identical except that: (1) they occur in different absolute positions; (2) an earlier series has one fundamental line on the left more than the next later series has. Thus only the K series has line A.

6. m fixes the number of the series; $n - m$ fixes the number of each line in the series.

It is now easy to see that if a spectrum is cut up, the series will fit exactly over each other thus:



The infra-red series beyond the O series are ignored. In practice even the O series is generally ignored.

§4. Third Main Group of Facts

Moseley found that the X-ray spectra, which he discovered and photographed, contained the K series of lines. The measured wave-lengths of the K lines for seven elements are shown in the second column of the following table.

l = wave-length, n = frequency. Since frequencies are inversely as wave-lengths, $n = 1/l$. R = the Rydberg-Ritz constant (the universal wave-number).

Elements.	l (K Series).	$\frac{n}{R}$.	$\sqrt{\frac{n}{R}}$.	Differences of $\sqrt{\frac{n}{R}}$.
Na	11883·6	76·683	8·759	
				·853
Mg	9867·75	92·348	9·610	
				·856
Al	8319·40	109·535	10·466	
				·856
Si	7109·17	128·182	11·322	
				·859
P	6141·71	148·374	12·181	
				·857
S	5360·66	169·992	13·038	
				·859
Cl	4721·85	192·99	13·897	

Similar results are obtained with all the other series, and with all the other elements, within the limits of experimental error. (The ratio n/R is a convenient number independent of the units of measurement.)

Thus the amazing discovery was made that the 92 elements may be arranged in order in such a way that the square roots of the frequencies of the corresponding spectrum lines form an A.P. If we multiply $\sqrt{n}$ by such a constant as to bring the common difference to unity, we get the series of *atomic numbers* 1–92. Thus the different elements in the atomic series climb the ladder of frequency by regular and equal steps.

Moseley's discovery first made it possible to remove several points of doubt from the originally arranged periodic system, since the fixing of the atomic numbers also determined exactly the number of elements in each period. The number of elements in the successive individual periods, as shown in the usual horizontal rows in the complete periodic scheme, are found to be 2, 8, 8, 18, 18, 32, or exactly twice the values of the squares of the numbers 1, 2, 2, 3, 3, 4.

From these three main groups of facts, physicists have striven to discover the inner secret of the atom. There have been other facts as well, especially those derived from radioactivity, but atomic weights, spectral lines, and atomic numbers have been the really substantive facts which physicists have used for building up their hypothetical models. But before we come to the models, it is necessary to refer to the Quantum theory.

§5. The Quantum Theory

If we push a piston into a gas-jar, we experience an opposing pressure, which increases as we push the piston inwards. We feel that the increased pressure we exert is increased *continuously*, not by a series of discontinuous jerks. But what of the opposing pressure due to the enclosed bombardment of air molecules? If we accept the kinetic theory of gases, as presumably we must, the bombardment, as the word implies, is due to a series of separate blows, uncountably numerous, it is true, yet necessarily *discontinuous*. It looks as if, in the case of at least gas molecules, the old idea of unbroken continuity of pressure has to be given up.

The form of a spectrum seems to teach us that the radiation emitted by hot bodies into space is not energy of a simple form, but is made up of a number of elementary radiations of different wave-lengths (λ) and frequencies (ν), though the velocity is constant ($v = n\lambda$). The result is a spectrum of all wave-lengths and frequencies.

But every attempt to establish a law of radiation on a basis of the accepted principles of classical theory had failed. Wien's well-known law of radiation was based on calculations from Maxwell's law of distribution of velocities among gas molecules. Tested experimentally, the law was found to hold good for only high frequencies, that is for short wave-lengths. For waves of small frequencies, that is long wave-lengths, discrepancies were detected, and these discrepancies were found to be systematic. Planck was rather surprised, for his own investigations had confirmed Wien's law. But in a new investigation over which he took years, Planck tried to penetrate into the realm of electrodynamics with thermodynamic principles. To ensure agreement with observation and experiment, Planck finally saw himself compelled to take a bold step leading right away from the ordinary principles of the wave theory, and he advanced the hypothesis that a radiating substance constituted a system of linear electromagnetic *oscillators*, amongst which the whole of the available energy must be distributed. But he imagined this energy divided up into a discrete number of finite energy elements (*energy quanta*) of magnitude ϵ, and he assumed these quanta to be distributed at random among the individual oscillators exactly as a given number of balls may be distributed at random among a certain number of boxes. He thus turned the radiation problem into a problem of *probability*—a definite amount

of energy to be divided among the oscillators *according to chance*, and the mean value of the energy of the oscillators to be calculated. The radiated energy—it might be light, it might be X-rays—always travelled as *indivisible* units, any one of which represents a complete store of energy, but of which no fractions are possible. On this hypothesis, energy is essentially *discontinuous*.

Planck's hypothesis may be thus stated: the energy of radiation, of any frequency ν whatever, can be emitted and absorbed only in whole multiples of an elementary quantum of energy:

$$\epsilon = h\nu, \text{ or } h = \frac{\epsilon}{\nu} = \frac{\textit{radiation energy}}{\textit{radiation frequency}},$$

where h is Planck's quantum of action. From actual radiation measurements, Planck succeeded in determining the value of his constant:

$$h = 6{\cdot}55 \times 10^{-27} \text{ erg. sec.}$$

The quantum of action is a definite natural constant, measurable with precision. It is closely associated with the angular momentum of an electron hypothetically revolving inside an atom.

The essence of the quantum theory—that the energy of the oscillators of the natural frequency ν is not a continuously variable magnitude but is always an integral multiple of the element of energy $\epsilon = h\nu$—is so novel that those of us who were brought up on the classical theory of Newton and Maxwell instinctively shrink from accepting it. But if the energy of the Planck oscillator is only to amount to integral multiples of $\epsilon = h\nu$ and therefore can have only the values 0, ϵ, 2ϵ, 3ϵ, &c., then, since the oscillator changes its energy only by emission and absorption, the conclusion seems inescapable that oscillators cannot absorb and emit amounts of energy of *any* magnitude, but only whole multiples of ϵ. This conclusion is in direct contradiction to classical electrodynamics.

A further hypothesis was advanced in 1905 by Einstein, namely, that not only do energy quanta play a part in the interaction between radiation and matter (oscillators), but that radiation, when propagated through a vacuum or any medium, itself possesses a quantum-like structure; in other words, radiation consists of indivisible *radiation quanta*, light behaving just as if it were composed of particles, sometimes called light quanta. Thus, according to this theory, when the energy is being propagated from the exciting centre, it does not emerge in the form of a succession of spherical waves over

ever-increasing volumes of space, as the wave theory asserts, but remains concentrated in a finite number of energy particles which move like material structures. Several investigations forced Einstein to this strange conception, which clashes with all the observations that appear to support the undulatory theory.

Thus it would seem that all forms of radiation energy, including light, are discontinuous, just as is electricity.

Planck's hypothesis and Einstein's hypothesis were advanced a generation ago, but even now physicists have no very clear understanding of the principles underlying the quantum theory though their faith in the theory is strong. Historically, the theory is largely of mathematical origin, and parts of it are, physically, still very obscure. Its main postulates seem to be arbitrary.

§6. The Atom as an Astronomical System

Readers are doubtless familiar with the general history of Radioactivity. The artificially excited variety of radioactivity was discovered by Röntgen a few months before Becquerel discovered the spontaneous variety. Becquerel's work was extended by Madame Curie. Less than three years afterwards, the ionizing power of X-rays was utilized by J. J. Thomson, Rutherford, and others, to turn rarefied air into an electrolyte, and, by determining its conductivity, and in other ways, to help measure the atomic charge of electricity. At quite an early stage, physicists discovered that particles which always have the same electric charge and the same mass can be severed from the atoms of all elements. The particles were given the name of **electrons.** The mass (m) was estimated to be 1/1847 of that of an H atom, and the charge (e) to be $4{\cdot}77 \times 1/10^{10}$ electrostatic units. The charge is sometimes described as the elementary quantum of electricity. From the first it was believed that those electrons were probably the elementary units of which all atoms were built up, and physicists eventually set to work to invent an atomic model.

The evidence for the actual existence of these primitive particles (electrons) seems to be at least as trustworthy as the evidence for the existence of atoms themselves. But there is at least one well-known chemist who denies this; he stoutly defends the existence of atoms but emphatically denies the existence of electrons. This is not quite reasonable, for, relatively, the difference in the two

orders of magnitude is too slight to be worth considering. (The mass of an H atom is estimated to be $1{\cdot}66 \times 10^{-24}$ gm., and that of an electron $0{\cdot}9 \times 10^{-27}$ gm.)

The origin of most of the atomic models is ultimately traceable to Wilson's well-known photographs of the phenomena which occur during the passage, through laminæ of matter, of the X-rays emitted by radioactive substances. Most of the positively charged particles of the α-rays seem to pass through the atoms of matter without any change of direction, but towards the end of the otherwise straight paths of a small number of the particles may be seen a sudden sharp bend. To a casual observer, these bends would have no significance, but they set Rutherford on a line of inquiry that immediately interested all the leading physicists of the world and have kept them busy ever since.

Rutherford traced the deflections to repulsion in electric fields produced by the deflecting atoms. But inasmuch as the great majority of the α-rays found their way, unimpeded, through the atoms, the volume of the atom must be relatively large compared with the source of those electric fields. And since electrical forces are inversely proportional to the square of the distance, it was concluded that each deflecting atom possesses a positively charged **nucleus** occupying only a very small part of the **volume** of the atom, in which almost the whole of the **mass** of the atom is concentrated. The magnitude of the deflections was observed to increase with the atomic weight of the deflecting element, and the intensity of the deflecting field must therefore also increase with the atomic weight. If we consider the field produced by a point-charge concentrated in the nucleus, and if we suppose this charge to act according to Coulomb's law, we may evidently calculate the magnitude of the charge which causes the observed deflections. At Rutherford's suggestion, Chadwick measured the deflections caused by the laminæ of platinum, silver, and copper, and he succeeded in determining the charges which must be assumed to exist in the corresponding nuclei. For the three elements named he obtained, respectively, the numbers 77·4, 46·3, and 29·3. These numbers agree, within the limits of error, with the Moseley positions of the three elements in the atomic system, viz. the atomic numbers 78, 47, and 29. The estimated charges (77·4, 46·3, 29·3) must obviously represent integral multiples of the elementary charge e. Numerous other experiments gave the same result, and Rutherford's fundamental

hypothesis, viz., *the nuclear charge is numerically equal to the atomic number*, seems to be firmly established on an experimental basis.

The Hydrogen atom, the lightest of all atoms, has only one electron, and its nucleus, called a **proton** is regarded as a second primitive particle. The nuclei of the atoms of all elements contain a whole number of protons (H nuclei), and the *mass* of any element is an integral multiple of the mass of a proton. H nuclei (protons) are usually ejected when the nuclei of any atoms are artificially disintegrated. Until within the last very few years the available experimental evidence seemed to show that the nucleus of an atom consists of two distinct parts, (1) an inert mass of inactive protons and electrons, and (2) a number of *charged* protons, the latter maintaining an equal number of electrons in positions outside the nucleus; the *atomic weight* was equal to the whole number of protons, and the *atomic number* to the number of active protons (usually about half the total) and therefore, of course, to the number of outside electrons.

But other primitive particles have now been discovered, and the nucleus is evidently less simple. One of them is **the neutron** (symbol $= {}^{1}_{0}n$) which has unit mass (= mass of proton), but it has no charge and therefore no electric field. It now seems possible that an atomic nucleus is made up entirely of protons and neutrons, a neutron perhaps consisting of a proton and an electron. But the more recent discovery of another primitive particle, the **positron**, made in connexion with researches on cosmic rays, complicates the problem further. The positron is the counterpart of an electron; it has the same insignificant mass, but is a *positive* particle; its life is very short, and it is supposed to disappear by combining with an electron. Still another primitive particle, the *neutrino*, has been discovered, or at least is strongly suspected to exist.

The so-called α-particles are helium nuclei. The **deuteron** (or **diplon**) is the nucleus of the heavy isotope of hydrogen; it has the same nuclear charge as ordinary hydrogen, but it has twice the mass number (2 units). Swift deuterons are much used for effecting transformations. A deuteron is perhaps a proton and a neutron bound together. (Symbol = D).[1]

Since the atoms as a whole are electrically neutral, we may safely assume, although the complete constitution of their nuclei is still a little uncertain, that the positive charges of these nuclei are compensated by the negative electrons surrounding it.

[1] For details see Max Born's *Atomic Physics*.

The question therefore arises, how can these electrons maintain themselves in position, attracted as they are by the nuclear charges.

Most chemists favour some kind of *static* model of the atom, and the most satisfactory one of this type has been put forward by the distinguished American chemists Professor **G. N. Lewis** and Professor **Irving Langmuir**. In this model the external electrons are stationary and occupy definitely assigned positions in a succession of spherical shells, in accordance with the "Periods" of the Periodic Law. It is a model which affords a very satisfactory explanation of chemical affinity.[1]

But most physicists favour a *dynamic* model of the atom. They ask if the attractive action of the nucleus will not cause the external electrons to fall into the nucleus, and they think that the solar system suggests, by analogy, a satisfactory answer. The earth fails to fall into the sun because of the same attractive force. If we transfer the idea to the atom, we may picture the atom as a planetary system in which the electrons are the planets and the nucleus is a central body around which they revolve.

For many years the analogy of the solar system has appealed to physicists strongly, but it must be borne in mind that if such atomic systems actually exist they are inconceivably minute. An atom is not, by a very, very long way, of the same order of magnitude as, say, the tiniest visible specks of dust; to compare those two things is like comparing the volume of a cherry with the volume of the earth.

The earliest suggested atomic models of the solar system was based on Faraday-Maxwell electrodynamics, but they would not work. Eventually Niels Bohr of Copenhagen suggested one of an entirely new type, and that held the field for some years.

If we accept the theory that the earth and the other planets were born of the sun, by attraction from a passing star, it is easy to see that they fell into their respective orbits in accordance with the respective energies concerned. But they might easily have fallen into any other orbits, had the "pull" of the passing star been greater or less. The earth's distance, for instance, might easily have been 90 or 94 millions of miles instead of 92. This is entirely in accord with the principles of classical dynamics. It was this kind of

[1] See *The Endless Quest*, pp. 479-483.

scheme that Bohr saw he could not adopt for an atomic model.

The new departure that Bohr made was to confine his revolving electrons to particular and specified orbits. There might be more than one orbit, but these must be definitely related spatially, and between them there could be no others. If an electron changed its orbit, as it might, it must be from one to another of this particular system, but in any orbit the frequency of revolution must be constant.

It was the quantum theory that suggested to Bohr these discrete orbits. In 1913, he advanced the hypothesis that the structure of the atom must be conditioned fundamentally by Planck's elementary quantum of action. He considered first the hydrogen atom, and he equated to the elementary quantum of action the product

momentum of electron × *circumference of orbit.*

Then, by making use of the fact that the electrical attraction between the nucleus and the rotating electron must be balanced by the centrifugal force, he arrived at sharply defined values for the orbital radii and for the velocity of the electron. Bohr further assumed that there were abnormal states of the hydrogen atom, in which the product is equal to an integral multiple of the quantum, the fundamental state being accordingly known as a one-quantum state. For each of the possible states, Bohr's theory gave a definite value of the energy, and, on the assumption that during the transition between any two "permissible" states, a light quantum equal to the energy difference of the two states is emitted or absorbed, Bohr was able to calculate all the frequencies of the hydrogen spectrum lines in complete agreement with the frequencies determined by actually measured wave-lengths.

At first Bohr restricted himself to circular paths for the electrons, and thus only those paths were permissible for which the angular momentum is a whole multiple of $h/2\pi$. This gives a family of discrete concentric circles around the nucleus, with radii which are related to one another as the squares of the natural numbers (1 : 4 : 9 : 16, &c.). Such possible radii are directly suggested by the Balmer formula, and doubtless Bohr's successive hypotheses were, at least indirectly, based on this formula as a foundation. It seems highly probable that the formula gave him the first hint that Planck's quantum of action was the key to the whole situation.

The "permissible" paths are "stationary", "stable states of motion". The stability is gained by making the novel assumption

that the electron—in striking contrast with anything that the classical theory has taught us—*cannot radiate when in the stationary paths*. Since all loss of energy is in this way abolished, the electron can continually revolve in such a quantum path and is thus a perfect perpetual-motion machine. The classical radiation of the atom disappears.

But when an electron passes from one permissible quantum orbit, in which the energy is, say, E_1, into another permissible path with energy E_2, energy amounting to $E_1 - E_2$ is radiated in the form of an energy quantum $h\nu$ of homogeneous monochromatic radiation. By Bohr's hypothesis, the frequency of this radiation is $\nu = (E_1 - E_1)/h$.

The various hypotheses of Bohr's may seem very far-fetched, but if we apply them to a Hydrogen atom, in which an electron revolves round a positive nucleus with a charge k, we get for the frequencies of the spectral lines which the electron emits in passing from the nth to the mth quantum path, the empirical formula

$$Rk^2\left(\frac{1}{m^2} - \frac{1}{n^2}\right),$$

where R is the Rydberg constant and m and n are whole numbers.

For Hydrogen, $k = 1$.

If $m = 1, n = 2, 3, 4 \ldots$, we get the ultra-violet series of H lines.
If $m = 2, n = 3, 4, 5 \ldots$, we get the " visible " series of H lines.
If $m = 3, n = 4, 5, 6 \ldots$, we get the infra-red series of H lines.

In this way Bohr accounted for the K series of spectral lines in the ultra-violet, for the L series in the visible spectrum, and for the M, N, O and perhaps other series in the infra-red. He still had to explain why the A line of the K series is missing from all the other series, why the B line of both the K and L series are missing from the M, N, and O series; and so on.

He assumed that the K orbit was the innermost orbit, a one-quantum orbit, the orbit having the highest frequency and the shortest wave-length. The other orbits, two-quantum (L), three-quantum (M), &c., follow outwardly in order, each with its characteristic rate of revolution. The innermost (K) orbit is the most stable, and here the electron is normally found.

By sudden excitation from without (heat motion, collision, electric fields, cathode rays, X-rays, &c.), an electron is apparently jerked out from an inner orbit into an outer orbit, but it then has

less stability. Left to itself, it jumps back sooner or later into some inner orbit. During this jump back, energy is liberated, and is emitted in the form of monochromatic radiation, i.e. radiation of one wave-length. Only during these transitions is the light-energy radiated. The energy emitted is the difference of the energy in the initial and final orbits. The frequency of the spectral lines produced by the transition is thus determined.

Thus every spectral line is produced by an electron jumping from one orbit to another. The particular rate of vibration depends both on the orbit jumped from and the orbit jumped into. A study of the spectra enables us to specify these two orbits.

An electron revolving steadily in an orbit does not disturb the æther. But a jumping electron gives a sort of kick to the æther and sets up a wave. The frequency of this wave depends on the violence of the kick, i.e. on the energy liberated.

To excite K radiation and to produce K lines, an electron must be jerked from the K orbit either into an outer orbit or away to "infinity" (a relatively great distance). The K "shell" of electrons (only 1 in H) tries to complete itself again, and the missing electron may be furnished from the L, or the M, or the N, or any other orbit. Whereas the process of excitation was accompanied by a gain of energy, the converse process takes place with loss of energy. According as the missing electron returns to the K orbit from the L, M, or N orbit, the energy set free will be different in amount. Hence there will be various possible K radiations, each of them represented by a definite wave-length, and all of them together giving the K series of lines. The K series occur high up in the violet.

To excite L radiation, an electron must be jerked out of the L orbit into an outer orbit. The L lines are the original Balmer series and occur in the visible spectrum. The characteristic red line (Fraunhofer C) is produced by a jump from the M orbit to the L orbit; the blue line, by a jump from N to L.

And so on.

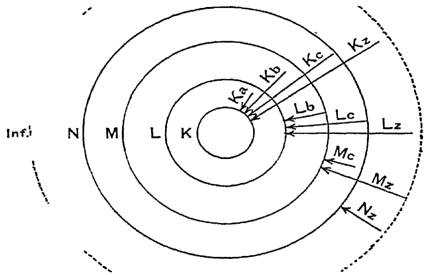
The *series*, and the positions of *lines in series*, are thus determined:

1. The *series* is determined by the orbit *into* which electron jumps.

2. The *lines in a series* are determined by the orbit *from* which electron jumps.

3. The *fundamental* (lowest) line of a series represents a jump from the next orbit.

4. The *head* (highest) line of a series represents a jump from "infinity". The results may be shown diagrammatically, thus:



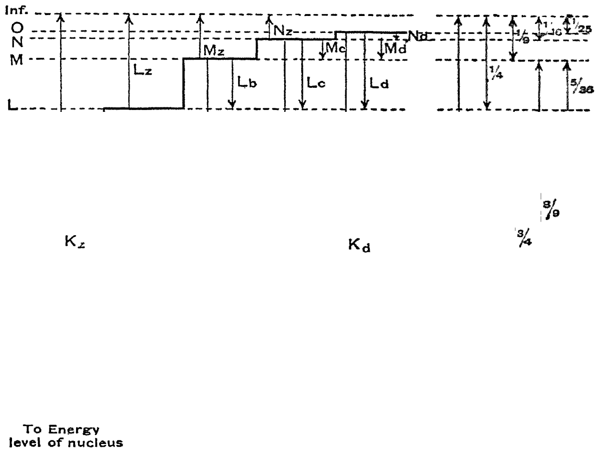
Since each series is connected with one orbit, why is there a series of lines instead of only one line?—If electrons all jumped from the same outer orbit into (say) the L orbit, their radiation *would* consist of only one line. But if the H is strongly agitated, electrons will probably be jerked into many of the outer orbits; hence the jumps back represent different energies, different frequencies, and different lines. We are always dealing with *many* H atoms, not with only one.

If the additional energy given to a revolving electron is, (1) as much as it already possesses, it flies away to infinity; (2) less than this, but equal to a critical value, the electron changes its orbit; (3) less than the critical value, nothing happens.

Since the radii of the orbits are represented by square numbers, the total *energy* corresponding to each orbit (which we know to be inversely as the distance) will be represented by the *reciprocals* of the square numbers. Thus, if the total energy associated with the K orbit is 1, that in the L orbit is $\frac{1}{4}$. Hence the step or difference in the energy from K to L is $\frac{3}{4}$; from K to M, $\frac{8}{9}$; from L to M, $\frac{5}{36}$;

and so on. The energy in orbit N is $\frac{1}{16}$; hence to make an electron jump from K to N, $\frac{15}{16}$ of its energy must be supplied to it. (A very little more would make it escape altogether.) And that is the amount of energy that will be emitted when the reverse step is taken.

If the orbits are represented by horizontal lines, the energy differences between the levels are easily indicated. In the succession of energy steps, the difference in height between two steps shows



the energy liberated when an electron jumps from a higher to a lower step.

For lines of a series to be emitted *at all*, there must be electrons in the jumping-off orbit. If very few of the atoms contain such electrons, the corresponding lines will be faint.

It was Planck who saw that the connexion between the radiating atoms and the energy they emitted could not be accounted for by any theory of *continuous* emission. Either definite portions of energy are emitted or none at all. Regularity and law remain, but everything takes place in *steps*, in *gushes*. The steps are not equal.

Bohr's ingenious hypotheses accounted fairly satisfactorily for the principal Hydrogen spectrum lines; they were also in harmony with such scanty experimental evidence as was available and were in harmony with calculations based on energy considerations. But it is certain that the Hydrogen atom is really a much more complex thing than the model thus created. For instance, the number of spectrum lines is very great, and each one of them has to be explained somehow. Every line must have a definite origin. And when atoms other than those of hydrogen are considered, it is no longer a question of a single electron: there may be as many as 92.

Such difficulties gradually led to the creation of a model more and more complex, and Sommerfeld's *Atomic Structure and Spectral Lines*, the standard work on the subject, is really a history of this creation. Circular orbits gave way to elliptical orbits; with the nucleus at a focus, these orbits were given different planes; the electrons were given right-handed and left-handed spins; and by ringing the changes on all these and other factors, it became possible to explain any possible " state " of an atom by which any particular spectrum line might be produced. For each of these " states " had by Pauli's principle to be unique, and different from every other state.

The Hydrogen atom was naturally regarded as the prototype of all other atomic models, but in the case of that atom we are dealing with the simple mathematical problem of two bodies. (The earth and the sun, if isolated, would be another such problem.) In all other cases we are dealing with the very difficult (and unsolved) problem of three bodies or more. Imagine the mathematical difficulty of accounting for the antics of 92 revolving electrons all well excited!

Any hypothesis to be complete had to take account of the " periods " 2, 8, 8, 18, 18, 32 of the periodic law. Did these successive groups of electrons occupy successive rings around the respective atomic nuclei?

The whole story is much too long to tell here. But it soon became clear from investigations by Born, Landé, and others that the whole conception of the arrangements of the electrons into plane rings did not agree with fact. That there was symmetry was fairly certain, but the symmetry was spatial in three dimensions. We have already referred (in connexion with the structure of the statical atom) to the possibility of the electrons being arranged in a series of shells,

corresponding to the periodic grouping. From the number of elements in the successive rows of the periodic table (2, 8, 8, 18, 18, 32), it has been inferred that a shell characterized by the quantum number n could not contain more than $2n^2$ electrons. For example, a shell containing $2 \cdot 3^2 = 18$ electrons would be regarded as full.

Although physicists have not yet fully solved the problem, they have made substantial headway. That in the atom there is a definitely limited number of discrete mechanized and electrical systems characterized by quantum conditions, differing entirely from the infinite continuity of classically possible systems, thus much appears fairly certain. But what brings about this discontinuity in nature? *We do not know.*

The student of scientific method should make himself familiar with the post-war work on transmutation. The experimental work is novel, and the inferences drawn from the resulting data are far-reaching. But the reader must first discriminate between the artificially produced rays of the vacuum tube and the natural rays of radioactivity. He must be familiar with the nature of *isotopes.*

	Character	Electric charge	Artificial Rays (Vacuum discharge tube	Natural Rays (Radioactive)
1	Corpuscles	Positive	Positive or Anode	α-rays (helium ions)
2	Corpuscles	Negative	Cathode (electrons)	β-rays (electrons)
3	Waves	Uncharged	X-rays (very penetrating)	γ-rays (very penetrating)

He should know something about the modern manner of producing very high voltages, about the apparatus used for bombarding atomic nuclei, about the projectiles commonly used (protons, α-particles, neutrons, and deuterons), in short with the main facts of the new chemistry generally.

Nuclear equations differ in appearance from the older and more familiar type of chemical equations. The figures *over* the symbols represent the *mass* weight (i.e. the rounded off atomic weights) of the element (or rather of the appropriate isotope), the figures *under* represent the atomic number. In both cases they add up in the usual way.

Here is an equation for the 7-isotope of lithium bombarded with protons, α-particles (helium nuclei) being produced.

$$\overset{7}{\mathrm{Li}} + \overset{1}{\mathrm{H}} \rightarrow 2\,\overset{4}{\mathrm{He}}$$

Here is another[1] for nitrogen bombarded with α-particles, an oxygen isotope being formed and protons expelled.

$$\overset{14}{\underset{7}{N}} + \overset{4}{\underset{2}{He}} \rightarrow \overset{17}{\underset{8}{O}} + \overset{1}{\underset{1}{H}}$$

(For a short general account of transmutation, see the author's *The Endless Quest*, pp. 501–9. For a more detailed account see Max Born's *Atomic Physics.* For detailed description of the apparatus used, see Andrade's *The New Chemistry.*)

CHAPTER XLI

The New Mechanics

§ 1. Particles or Waves? Clashing Evidence

By 1923, the conflict between the two rival theories of radiation, based on waves and particles, respectively, had reached an acute stage.

The æther was first brought into prominence when it became clear that light had to be explained as waves, and Lord Kelvin used great mathematical skill in postulating the very peculiar type of medium which alone could give exact agreement with the experimental laws of light.

Faraday long before had regarded electric and magnetic effects as stresses in a medium, and Maxwell showed that the same medium could do double duty, carry electric effects and transmit light. By means of purely electromagnetic processes, Hertz crowned the theory by actually producing waves which had the velocity of light and were, in fact, invisible light—the waves now used in radiotelegraphy. Later it was shown that X-rays are also invisible light, their wave-length being about 10,000 times as short as those of ordinary light.

When X-rays fall on the atoms of a gas, electrons are ejected from the atoms; or when light falls on a polished metal surface, electrons are ejected from the atoms of the metal. These are called photo-electrons. If the X-rays are monochromatic, all the electrons are ejected with the same energy, with the same speed. This energy does not depend on the intensity of the X-rays but only on their frequency. With diminishing intensity we obtain merely fewer

photo-electrons. Compare this with sea waves breaking on a beach and rolling the pebbles about; the more violent the waves, the more pebbles are thrown and the farther they are thrown. If the water waves behaved like light, an almost calm sea would throw a few pebbles as violently as a great storm throws them all. Obviously the light does not act as we usually conceive waves to act. Even with the feeblest light there is no detectable lag between switching on the light and the appearance of the photo-electrons.

It is difficult to see how a *wave* could give up its energy otherwise than continuously, and it was Einstein who suggested that light contained units of energy which behaved exactly like particles. When one collides with an electron we assume that it gives up its energy to the electron, which can then escape from (say) the surface of polished metal. All the quanta in a given light are assumed to be the same, and the stronger the light the more numerous they are. If light is thus conceived to consist of particles instead of waves, it is essential for the explanation that the quanta shall be so concentrated that one electron can catch a whole quantum. *Why should it?* This is the photo-electric paradox.

Since atoms can be made to emit light and since each atom emits its own characteristic wave-length, this is evidently a consequence of the structure of the particular atom, presumably of the arrangement of its electrons, and Bohr's theory did explain these wave-lengths. But the explanation assumed a behaviour of the electrons contrary to ordinary dynamics. Some of the things the electrons did seemed to be quite in accordance with old rules; and the laws of Newton and Maxwell explained them readily. But other things they did required a new set of rules altogether inconsistent with the old ones. For the construction of those new rules there seemed to be only one suggestive hint, and that was, the quantity h appeared whenever the atom broke the old rules; this seemed to suggest some sort of connexion with the photo-electric paradox.[1]

The necessity for a fundamental departure from the laws and concepts of classical mechanics is seen most clearly by a consideration of experimentally established facts on the nature of light. On the one hand, the phenomena of interference and diffraction can be explained only on the basis of a *wave* theory of light; on the other,

[1] For the connexion of h with the photo-electric effect, see Max Born's *Atomic Physics*, p. 71. See also *The Endless Quest*, p. 521.

phenomena such as photoelectric emission and scattering of free electrons show that light is composed of small *particles* (conveniently called photons), each having a definite energy and momentum depending on the frequency of the light. These photons appear to have just as real an existence as electrons. A fraction of a photon is unknown.

Light thus seems to have a duality of character.

But this remarkable duality of character applies not only to light but to electrons as well. If we consider such experiments as the diffraction of X-rays, the tracks of α and β rays emitted by radio-active substances, the diffraction of matter waves (for fifteen years β rays were regarded as streams of particles, but experiments by G. P. Thomson and others indicate that they can be diffracted and are capable of interference), the Compton-Simon effect, and the collision experiments of Franck and Hertz, the conclusion seems inescapable that matter as well as radiation sometimes exhibits the properties of waves and at other times the properties of particles.[1]

Thus *all* particles, electrons equally with photons, are in some way connected with waves which seem to control them and give rise, under suitable conditions, to diffraction phenomena. But it is obvious that a thing cannot be a form of wave-motion and be composed of particles at the same time; the two concepts are opposed. As with photons, so with electrons: their behaviour is such that *sometimes* they exhibit the properties of particles, *sometimes* the properties of waves. No mental picture that we try to form seems to be satisfactory.

§2. De Broglie and Schrödinger

We seem to have no option but to regard the waves and particles as two abstractions which are useful for describing the same physical reality. It is futile to try to picture this reality as containing both waves and particles together, and try to construct a mechanism which shall directly describe their connexion and account for the motion of the particles. What the new mechanics does is to formulate the underlying laws in such a way that we can determine from them without ambiguity what will happen under any given experimental conditions.

Only those things can be accurately described of which we can

[1] See Heisenberg's *Physical Principles of the Quantum Theory*

form clear mental pictures. We cannot visualize either the electron or the photon, for each is endowed with a sort of dual personality, a sort of Jekyll and Hyde. The contrary characteristics of the electron and of the photon do not seem to square with anything in our previous experience; there is a clashing of concepts, and language therefore refuses to provide an adequate description. But mathematics is not subject to the same limitations as is ordinary language, and it has been found possible to invent mathematical schemes which do seem entirely adequate to include the clashing wave-like and particle-like aspects of both the electron and the photon.

We may think of electrons as *particles*, their charge and mass and energy being always observed in particle form, not spread about continuously in space. But if we want to determine the path of a beam of electrons, and whether and how it is reflected by a crystal, we must treat the beam as if it were a beam of *waves*. These waves we call de Broglie waves, and we assume that they are propagated through space in much the same way as light waves.

When quantum mechanics is applied to a system composed simply of a freely moving corpuscle, the equations that define the state of the system are the ordinary equations for wave motion. This fact alone seems to be sufficient to give to the corpuscle many of the properties of waves, and to allow us to consider a corpuscle in a given state as associated with or controlled by a given wave.

De Broglie put forward the hypothesis that, since the twofold character of radiation (undulating and corpuscular) is also to be attributed to matter, a freely moving particle, electron or proton, with total energy E and momentum mv, should be regarded as equivalent to a plane wave of frequency ν and wave-length λ. The hypothesis has been strikingly confirmed by experiment. De Broglie's conclusion was that *any moving particle must be accompanied by a wave,* and he postulated that *the wave must control the motion of the particle.* Thus, instead of Newton's laws of motion, de Broglie's new view gives a motion governed by waves, though of course Newton's laws still hold good for the large-scale phenomena of everyday life.

Schrödinger (1926) used de Broglie's idea to build up a theory of wave mechanics. By finding the differential equations for de Broglie's waves, Schrödinger successfully grappled with many of the problems of quantum phenomena. Amongst other things,

he showed that it was meaningless to assign a definite path to an electron in an atom, and this deprived the Bohr orbits of their reality: the orbits could be regarded only as useful fictions. Light is still to be regarded as propagated in electromagnetic waves, but the energy of the light is concentrated in particles (photons) associated with the waves; and whenever the light does something (releases a photo-electron, produces a photo-chemical reaction) it does it as a particle.

The de Broglie theory as developed mathematically by Schrödinger does seem to reduce to some kind of order the chaos of explanations of the properties of atoms. Further, it deals effectively with the photo-electric paradox. Granting that there are, in fact, quanta or indivisible particles in radiation, they will inevitably be accompanied by waves which will guide them.

In short, if we accept the hypothesis (in some measure experimentally verified) that electrons behave as if guided by a train of waves, great simplification of theory results. Both electrons and photons are on precisely the same footing: they are particles governed by waves. The difficulties of physics in the earlier years of the century were largely due to our ignorance of this dual character. We had got into our heads the wave aspect of light, and the particle aspect of electrons, and were running each to the exclusion of the complementary view.

But in spite of this one point of strong resemblance, the electron and photon are otherwise essentially different. The electron has an electric charge, and is therefore influenced by magnetic and electric forces in a way that the photon is not. The photon always travels (*in vacuo*) with a speed of 300,000 km. a second; the electron can travel with any speed less than that.

§3. Heisenberg and Dirac

The Bohr-Sommerfeld theory of the atom left many atomic properties undetermined, and Bohr suggested that classical models might be used as an aid to the discovery of the correct algebraic rules for describing quantum phenomena. This rather revolutionary suggestion inspired a group of keen young workers, among whom was Heisenberg, who did much to transform previous tentative methods into a strict mathematical discipline. It was a little before Schrödinger's theory was propounded that Heisenberg

(1925) laid the foundation of his own theory of Quantum Mechanics, by setting up a scheme which allowed the *observable* amplitudes and frequencies of the radiation emitted by atoms to be calculated. Heisenberg's method was a severely logical mathematical method, and, with the assistance of Born and Jordan, an abstract symbolic scheme (matrix theory) was developed (1925–6), quite novel to physicists. Various alternative forms of the same methods were soon evolved, of which the most important was that of Dirac (1928). Yet the matrix theory of quantum mechanics left many problems untouched.

Mathematics is a tool specially suitable for dealing with the abstract concepts of physical science, and for this reason a book on the new mechanics must be essentially mathematical. But the student must never forget that mathematics is *only* a tool, and that the physical ideas it represents must always be kept in the forefront of the mind.

It is a remarkable fact that in the de Broglie-Schrödinger waves and the Heisenberg matrices, the two mathematical lines of advance seem to converge to a common point. That methods so completely different in inspiration and mathematical technique should lead to practically the same result is an excellent illustration of the possibility of a set of experimentally given facts in a region of physics being arranged in two ways that are apparently different but are actually equivalent. It is true that the physical interrelations of the two methods are still obscure, but a clue was supplied by Born, who showed that in certain cases a function of the Schrödinger wave quantity expressed the *probability* of a particle being freed at a given point at a given moment. This idea led to the fusion of wave and matrix mechanics, and of the pseudo-wave and pseudo-particle models in the Probability Transformation theory of Dirac and Jordan. This theory represents a natural generalization of the earlier partial quantum theories; it is a set of general and abstract algebraic rules which, when applied to any given system, can be interpreted so as to present the calculation (1) of all the possible results of a given measurement; (2) of "transformation functions", by which the numbers representing the given initial conditions are transformed into an expression of the *probability* of any given result being obtained in a measurement made in the system. The theory is essentially one for only the competent mathematician.

§4. The Old Mechanics and the New

It is claimed that the new mechanics is based on a vast amount of experimental data. That is true, but most of the experimental results are of an indirect type, experiments which, directly, concern things unimaginably below the range of vision. The experimental evidence being so largely inferential is always open to some little suspicion. Mathematical schemes evolved from experimental results of this type, no matter how consistent and unassailable they may be in themselves, cannot be more certain in their final results than the original premisses from which they set out. Certain prominent mathematicians are now inclined to stand aloof, feeling that the quantum enthusiasts of the last ten years have got themselves tied up in a series of mathematical knots from which they cannot escape.

Has classical mechanics been overturned?

It is very difficult to balance the pros and cons. We seem to be able to fit into a mathematical scheme the observed facts concerning the nature of light, but we certainly cannot tell what paths are followed by the light quanta (photons), and we should feel profoundly dissatisfied with the whole quantum theory were it not for the recent discovery that electrons as well as photons have a dual nature, corpuscular and undulatory, and of course it is this discovery which is the basis of wave-mechanics.

A prominent physicist has pointed out that an electron no longer seems to have even an approximate boundary, and that therefore its size no longer seems to be definite. "When an electron is part of an atom, its waves seem to curl round in themselves until it occupies only the atom." "When it gets free of the atom, its waves seem to uncurl and to expand indefinitely." But how can we escape believing that it must have some sort of centre? When it produces any detectable effect, it does so as a particle.

What is the medium that transmits the electron waves? Are we faced with waves in empty space that do not fit into the series of ordinary æther vibrations? It has been gravely suggested that we should regard the waves as mathematical abstractions, as "ghost" waves. Ghosts as guides!

Matter is still supposed to consist of discrete units, but instead of these units moving according to laws which concern them alone, as did the laws of Newtonian dynamics, we have had to introduce

laws based on waves. Now a wave is essentially a *continuous* thing, even if the continuity is only mathematical. It is spread through space, not divided up into bits. Hence although the belief in the discontinuity of matter still holds, it has lost some of its robustness. As Professor G. P. Thomson says, continuity has crept in again by the back door.

The idea of the æther has also changed. The sole function left to it is to guide the quanta: they do the work.

In some way that we do not yet understand, the Newtonian mechanics does seem to need modification, it may be just a simplification, which however is only necessary when wave-lengths are very small.

We cannot but feel greatly impressed with the remarkable ingenuity which such mathematical physicists as Schrödinger on the one hand, and Heisenberg on the other, display in their theories. But although their results may be truly *symbolical* of the way in which nature works on a scale too small to be imaginable, the symbols steadily refuse to give up their secrets. We are still in the dark, and it is dishonest to pretend otherwise.

In spite of the amazing amount of work done during the last few years, we cannot yet say finally that classical mechanics has been superseded and that wave mechanics has come to stay.

CHAPTER XLII

Relativity

§1. A Suitable Course of Reading

Whatever we may think about wave mechanics, we must admit that Relativity has undoubtedly come to stay, and everybody interested in science and the methods of science should try to understand its far-reaching implications; otherwise a great deal that underlies modern scientific research cannot possibly be understood. But not every reader is likely to make himself really master of the subject; only a thoroughly competent mathematician can do that. Any reasonably intelligent person may, however, with a

little patient application, readily understand the "special" theory of Relativity, and may obtain a considerable insight into the "general" theory as well. Here is a suitable course of reading: Professor Rice's and Mr. Durell's little books; then Einstein's own elementary book (*The Theory of Relativity*); these to be followed by Professor Nunn's *Relativity and Gravitation*, and Professor Eddington's *Space, Time, and Gravitation*. These five books will satisfy most readers, but there is plenty of stiffer literature available for readers who are mathematicians.

The purpose of the following paragraphs is merely to help the reader to a right frame of mind when he settles down to the subject.

§2. Newton's Fame Undimmed

It is not so much that Newton was the first to use the calculus; that claim was disputed by Leibniz. Nor was he the first to conceive the exact relations between inertia and force: of these, Galileo certainly had an inkling. Long before, Kepler had had a suspicion of a universal gravitation; and the inverse square law had been mooted by Hooke before the *Principia* was born. The outstanding feature of Newton's work was that it drew together so many loose threads. It unified phenomena so diverse as (1) the planetary motions that had been exactly described by Kepler; (2) the everyday facts of falling bodies; (3) the rise and fall of the tides; (4) the wobbling motion of the earth's axis; (5) many minor irregularities in linear and planetary motions. With all these drawn into such a simple scheme as the three laws of motion combined with the inverse square law, it is no wonder that for a long period scientific speculation almost ceased. The universe seemed simple, and its main problems solved. During the next century there seemed little to do but develop Newton's dynamics formally. In short, Newton was faithfully followed until little more than a generation ago. Then came the clash between (1) the phenomena of aberration, and (2) the Michelson-Morley experiment. The obvious inference from the former was that the æther is stationary, and is therefore a possible reference frame for all measurements; but the equally obvious inference from the latter was that the æther is not stationary. Nobody felt satisfied with the one serious attempt that had been made to reconcile such contradictory inferences, viz. by means of the Fitzgerald-Lorentz contraction hypotheses. Einstein, in par-

ticular, disliked the idea of a *physical* contraction, and he set to work to devise a more acceptable explanation. Eventually, Einstein showed clearly that we may logically regard the contraction as a *subjective* contraction, depending on the transformations of our space and time reference frame.

§3. Our Natural Prejudices

We have spent our lives in making measurements and calculations in accordance with classical principles with which all our physical concepts are in harmony. We naturally shrink from questioning these principles, much as we should shrink from questioning the multiplication table. And yet these principles cover merely *old* experience. Why should there not be *new* experience, which refuses to square with the old principles? Clearly there is no reason at all. Naturally we tend to feel that if we question principles hitherto universally accepted, we are acting contrary to common sense. On reflexion it will be admitted that this is prejudice. Much of the work in physics during the last twenty years seems to be in flat contradiction to common sense, if by "common sense" we mean old experience. To this extent all great discoveries have contradicted previous common sense. The early scepticism shown towards Einstein is as easily understood as the violent hostility that was shown towards Copernicus.

§4. Relativity Frameworks

A framework of space and time is the system of location to which we appeal when we state, for instance, that an event is 100 miles distant from, and 10 hours later than, another. The terms space and time have not only a vague descriptive reference to (1) a boundless void, and (2) an ever-rolling stream, but they are also suggestive of an exact quantitative system of reckoning distances and time intervals. Einstein's first noteworthy pronouncement was that there are an infinite number of such systems of reckoning, exactly on all fours with one another. No one of these can be distinguished as more fundamental than the rest. And yet one of them does present itself to us as being the actual space and time of our experience, and we recoil from the other equivalent frames because they seem to us to be artificial systems in which distance and duration

are mixed up in an extraordinary way. This invidious selection is not determined by anything distinctive in the frame; it is determined by something distinctive in *ourselves*, by the fact that we are tied to a particular planet. *Nature* offers us an infinite choice of frames; *we*—quite naturally—select the one in which we and our petty terrestrial concerns take the most distinguished position. Our geocentric outlook has unsuspectedly and mischievously persuaded us to insist on this particular terrestrial space-time frame. Einstein's theory has ruthlessly exposed the fallacy of our attributing to our terrestrial reckoning of space and time a more than local significance. If, as may be possible in the distant future, our descendants are able to roam about space from planet to planet, they will probably be amused at the difficulty we had in learning to read the Relativity alphabet.

§5. Simultaneity

The fallacy of our old notion of simultaneity must be *thought out*. Suppose a man to die at the age of 80, 1000 miles from his birthplace. An inhabitant on a rapidly receding star might report the age to be 81 and the distance travelled to be billions of miles. A similar estimate would be made if we on the earth reported a like happening on the receding star. Relatively, the earth and star are receding from each other. Consider the earth and two such stars, all receding from one another, and all reporting the happening of events on the others. What about the attempt to discover absolute simultaneity amongst the reported events, then? Or look out of your window on to a busy street. The eye claims to see a hundred events all happening at the same moment. But clearly this is a fallacy. It is not the events that are happening in the instant *now* that the eye "sees", but the sense-impressions to which earlier events gave rise. All the events had to be reported by light-signals, and these take time. *All* the events happened before we could see them, and the more distant the event the earlier it happened. *We cannot dissociate time from space.* But this in no way tampers with our *local* instants which form the stream of our consciousness. Einstein's theory leaves entirely untouched that time succession of which we have intuitive knowledge. It freely admits the possibility of absolute simultaneity, but it emphatically denies that our *knowledge* of simultaneity can be more than relative. (See pp. 504–16.)

§6. Time as a Fourth Dimension

Although *time* is considered jointly with three-dimensional *space* as forming a four-dimensional continuance, the fact must be emphasized that time enters the fundamental Relativity formulæ quite differently from space. Time is not a fourth dimension of space; it is a fourth dimension of a mathematical *continuum*. Space of more than three dimensions is common enough in mathematics, but that does not mean anything of the nature of more than three physical *extensions*, or anything so irrational. Space and time have to be considered together simply because we cannot consider them apart. But space remains three-dimensional, and it is absurd to think of it as anything else. The usual method of expressing position and motion algebraically in three-dimensional space is by reference to three linear directions, mutually at right angles, like the edges of a cube that meet in one corner. The observer's point of view is the point where three such lines meet.

For mathematical purposes, a sphere may be spatially mapped out by three diameters mutually at right angles, intersecting at the centre O. Though we cannot use a fourth co-ordinate to represent *time*, we may adopt this device: imagine a series of spheres always to be moving inwards towards O with the velocity of light, and then to expand from O with the same velocity, this to take place quite uniformly however O may move in relation to other points of observation, so that the centre of the system of contracting and expanding spheres travels with the observer, and each observer has his own system of spheres. The approaching and contracting spheres contain within them the whole *future*; the receding and expanding spheres contain the *past*. The *present* is the passage of a sphere through O, the observer, when the space is concentrated at a point. The conception of a fourth dimension is thus not that of a simple spatial dimension like the other three, but is intimately associated with time and motion, and the observer's experience of it is simply the happening of events with the flow of time. Obviously to different observers the impressions of the *present* are not quite the same.

In Relativity equations, the fourth dimension is represented not by t, but by ict (where $i = \sqrt{-1}$ and c = velocity of light), and ict may be treated on an equality with the three space dimensions. Commonly, c is taken as unity. Thus time is merged with

space in an *equation*. The merging is merely a mathematical merging. Directly the i is removed from *it*, the time is completely dissociated from its companion and becomes independent again. (See pp. 511.)

§7. "World Lines"

A point of space at a point of time is called by Relativists a *world-point.* We may imagine that everywhere and everywhen in the " world " there is something perceptible, though it is advisable to avoid saying that that something is matter or electricity, or substance, or even æther. Fix the attention on a substantial point which is at a given world-point, x, y, z, t, and imagine that we are able to recognize that substantial point at any other time. Let dx, dy, dz of the *space* co-ordinates of this substantial point correspond to a time element dt. In this way we may obtain, as an image of the everlasting career of the substantial point, a line in the world, a *world-line,* as Minkowski calls it. The whole universe thus seems to resolve itself into world-lines.

Are the world-lines concrete or abstract? They are certainly not concrete.

The *concrete* is the sensuously given. It is that of which we are most certain in our ordinary life and in the laboratory. To us it is spatio-temporal, and *personal. Concrete* is the opposite of *abstract*; *real* is the opposite of *imaginary.* Both the concrete and the abstract are " real ". The criteria of " real " are (1) observed by all observers; (2) measurable. In this sense the abstractions of science are real, but they are not concrete. Different observers in different circumstances make different measurements. The world of the Relativist, including his world-lines, is abstracted from all local conditions and all personal peculiarities of terrestrial observers. It is *real* but it is *abstract.* As Professor Eddington says, " The external world is the common element abstracted from the experiences of individuals in all variety of physical circumstances ". It is the world of the non-individual observer. Science abstracts in order to obtain a universal standpoint so that an external world can be secured.

World is a misleading term. In common speech it often refers to just our planet. The term *universe* is preferable, that is, the matter-containing universe, including the stars and nebulæ, the universe contained (presumably) within a limitless void. Even

the term *æther* is becoming ambiguous. We no longer think of a Kelvin-Maxwell-Larmor æther, but of a Relativity space endowed with certain physical qualities of a directional nature and *perhaps* of a wave-carrying nature. When we leave mathematical abstractions and attempt to contemplate what is really happening, we seem bound to supplement the discontinuity of matter by a continuous energy-containing medium of some kind.

§8. Space Distortion

The reader who attempts to master the mathematics of Relativity (and really the whole theory is in essence mathematical) must be prepared for paradoxes. It will help to prepare his mind if he considers these three things: (1) Euclidean geometry is not strictly applicable even to the relatively trifling measurements we make on the surface of the earth. For we live on the surface of a *sphere*, and even our smallest so-called "planes" are really parts of a spherical surface. Hence any "plane" triangle is really a spherical triangle, and the sum of its three angles are therefore greater than two right angles. And so generally. This is not theory; it is sober fact. (2) The ordinary maps in an atlas are all distorted, for they represent parts of a spherical surface. The two-dimensional space of the spherical surface represented by the map is *strained*. The study of the motion of strained geodesics in such a map may be carried over (though the analogy is something of a trap for the unwary) into the four-dimensional space-time of Relativity, and thus some idea gained of what Einstein means when he identifies the presence of that part of space-time curvature which cannot be smoothed out, with the presence of matter. "Force" has no place in Relativity. Bodies are supposed to move as they do simply because that is the easiest possible movement in that region of space-time in which they find themselves, not because forces act upon them. Observed motions reveal not the presence of forces, but the nature of the geometry applicable to the region concerned. (3) The study of Poincaré's man in a convex mirror is particularly useful. The image of an external observer A may be regarded as an intelligent being B in the mirror. B applies to the images and their movements the same standard of measurements as A applies to the real objects in his own space. As A moves away to an indefinite distance, B approaches the principal focus F (half-way

between the centre and the surface of the sphere), but he can never reach it. If A measures off equal lengths farther and farther away from the mirror, he sees B doing the same, but B's measured lengths become shorter and shorter. If A places a ball in front of the mirror, B will be seen to place an oblate spheroid behind it. But how will B regard his own operations? He will be utterly unconscious that his measuring rod has contracted, and he will find it quite impossible to measure up his oblate spheroid and find that it is not a true sphere. To B, F seems to be at infinity, and all straight lines from F to the surface seem to be parallel. They correspond exactly to the parallel straight lines known to A outside the mirror. *B's space is obviously of a different nature from A's space.*

There is an element of danger in the use of such analogies, for they are apt to be regarded as real illustrations. They are nothing of the kind. They merely prepare the student for a rational approach to a new experience which he will find rather paradoxical, and for this purpose they are very useful.

§9. The Special and the General Theory

The "Special" theory, more accurately called the "Restricted" theory, could not be final, since gravitational phenomena and accelerated co-ordinate systems were not included. In Newton's law of gravitation it had been assumed that action at a distance was instantaneous, whereas in the Special Theory of Relativity, no influence could be propagated with a velocity greater than that of light, and Einstein felt that a theory of a more comprehensive character was necessary. Fundamentally, the General Theory rests on the *Principle of Equivalence*—that all the effects of a gravitational field are equivalent to the use of accelerated co-ordinate systems. Einstein said that the gravitation problem had not hitherto been solved because Euclidean geometry had been assumed to be applicable, whereas the problem requires the application of a more general space-time geometry which permits gravitational and inertial masses to be treated as essentially the same. For the solution of the problem, the mathematical weapons of Riemann and Christoffel, Ricci and Levi-Civita, were already to hand, and by 1915 the gravitational field equations which satisfied the necessary conditions, were evolved.

When Einstein announced his General Theory, he said that its

validity might be tested in three different ways. All three tests were promptly carried out by competent workers, and the results were all favourable to Einstein. *To that extent*, therefore, all Einstein's calculations were proved correct, and his theory therefore met with general acceptance. But, after all, Einstein's new gravitational law was the special interpretation of the result of the mathematical manipulation of certain measured quantities rather arbitrarily selected. *Was this interpretation necessarily correct?* Cosmologists set to work on the assumption that it was, and they built up universes, expanding and others, of a startling kind. But Professor A. N. Whitehead, one of the world's few master mathematicians, was very sceptical, and he suggested an alternative and equally acceptable interpretation. And now Professor E. A. Milne has given us his *Relativity, Gravitation and World Structure*, criticizing Einsteinian Relativity because it is mathematically developed from a purely conceptual basis and is not expressible in terms of observable quantities. Milne's working hypothesis is that the geometry of space-time can be taken to be that of the *Special* Theory of Relativity, and that the laws of astronomical dynamics can be validly expressed in this setting. Milne seems to look upon the General Theory as unnecessary. From the standpoint of observational astronomy, the cosmology which Milne has developed certainly seems to be far more acceptable than any of the Relativist cosmologies.

§ 10. Newton's and Einstein's Work compared

Einstein's gravitation theory not only includes all the results obtained by the use of Newton's inverse square law, but it accounts for various minute deviations from the law, and it predicted effects which have since been confirmed. That these deviations really are minute may be gauged from a typical instance—the respective acceleration values calculated for the planet Mercury: Newton's calculated value was increased by Einstein's gravitation equation to only the extraordinarily small amount of $1/10^8$ of itself. That Newton's calculation should be accurate to one hundred-millionth part is remarkable. For all *practical* purposes, Newton's laws still hold.

The theory of Relativity has but a slender empirical basis; it is essentially mathematical, but its successful predictions at first tended to silence the critics. No forecast can be made of its future empirical validity, and science will always demand such validity

as a final test. But any concept which permits of the uniformity of nature being expressed completely in mathematical form is necessarily of great physical significance.

CHAPTER XLIII

Causation or Indeterminacy?

§ 1. Causation

We may conveniently quote from p. 161: "To apprehend causation, we must first distinguish the elements before they have come together. And thus we get to perceive what may be called the conditions. But these conditions, when asunder, are not yet the cause. To make the cause they must come together, and their union must set up that process of change which, when fixed artificially, we call the effects. Though the effect follows, it follows immediately. Between the coming together of the separate conditions and the beginning of the process there is no halt or interval." And from p. 149: "We know the cause as *productive* of the effect, or we do not know it at all; and we know the effect as *produced by* the cause, or we do not know *it* at all."

Causation is usually interpreted as essentially serial—as a series of events a, b, c, d, . . ., wherein a, itself somehow produced or preceded, produces or invariably precedes or necessitates b, c, d, . . .; their relation remains fundamentally serial, whether merely as an invariable temporal sequence or otherwise. This is incontrovertible, though we feel it is inadequate.

But certain physicists no longer agree that the Law of Causation, or the Principle of Causality as it is sometimes called, is anything like so simple. They urge that, at least in atomic physics, the law of causation is statistical—that laws are obeyed by crowds of individuals independently of the characteristics of the individuals in the crowds. They maintain that the old and simple causational principle must now be restricted to large-scale events. It is of course true that when we observe electrons we observe them in vast crowds; we cannot observe one in isolation. Our inferences have to be drawn from what the crowds do. But because we cannot

discover what causes a particular electron to jump (if an electron does jump), it is speculative—it is rash—to suggest that causation has ceased to operate.

§2. Atomic Physics and Probability

When an observation is made on any atomic system that has been prepared in a given way and is then in a given state, the result will not in general be determinate; that is, if the experiment is repeated several times, it will be found that each particular result will be obtained a definite fraction of the total number of times. We can therefore say that there is a *definite probability* of its being obtained any time the experiment is performed. This probability the *Theory of Probability* enables us to calculate. In special cases the probability may be unity, and the result of the experiment is then quite determinate.

In making an experiment, the observer necessarily creates a great disturbance amongst vast crowds of electrons. The next time he performs the experiment, no matter how careful he is to repeat the former conditions exactly, it is highly improbable that the same disturbance will be made as before. The lack of determinacy may therefore be ascribed to the disturbance which the observation necessarily makes, and the apparent failure of causation is, from this point of view, due to a theoretical unavoidable clumsiness on the part of the observer. Heisenberg's Principle of Indeterminacy asserts that it is impossible to determine *both* the position *and* the velocity of an electron accurately at the same time; whichever of them we try to measure, the process affects the other. But experimentally, of course, it is impossible to determine either. The position or the velocity of an electron does not signify the same thing as the position or the velocity of a planet or of a cricket ball. It is something purely hypothetical.

In order to co-ordinate a definite cause with a definite effect, it must be possible to observe both without disturbing their interrelations, for clearly the law of causation can be defined for only isolated systems. In atomic physics, not even approximately isolated systems can be observed, and therefore the law of causation cannot strictly be made to apply. Since the geometric or kinematic description of a process implies exact observation, it follows that such a description of an atomic process necessarily precludes the

exact validity of the law of causation. Our picture of the process is bound to remain indeterminate, simply because we cannot decide other than arbitrarily what objects are to be considered as part of the observed system and what as part of the observer's apparatus.

§3. Does Indeterminacy imply "Uncaused"?

There is this essential difference between the principle of causality as applied to classical theory and indeterminacy as applied to the quantum theory: in the classical theory, causal relationships of phenomena are actually described in terms of space and time; in the quantum theory, of two things, one: either we may describe phenomena in terms of space and time, but then the principle of indeterminacy applies, or, the causal relationship may be expressed by mathematical laws, but then a physical description of the phenomena in space-time is not possible.

A certain number of physicists are urging the adoption of the hypothesis that intra-atomic movements are not determinate in the sense that they are not strictly caused but are only *conditioned*, that is, that they are partially free and therefore show a partial spontaneity; they maintain that a certain degree of spontaneity is quite as legitimate as a scientific hypothesis as strict determinism or causation.

It is, in fact, quite seriously suggested that although we may apply the laws of probability to electronic jumps from orbit to orbit in the atom, and so discover laws of the nature of statistical averages which will determine the number of jumps in a given period, yet the changes constituted by these jumps are not caused changes. Now it is quite true that we have no means of finding out whether a particular electron will jump and when. But it seems a little irrational to suggest that the electron decides for itself when it will jump. We may readily admit that the principle of indeterminacy must be accepted, but the indeterminacy should be ascribed to our ignorance of the facts, not to the irresponsibility of the electrons. On any atomic investigation, the interaction between the processes of measurement and the measuring instrument imposes limitations, and the formulation of these limitations constitutes the principle of indeterminacy. But this indeterminacy connotes uncertainty (really a preferable term); it signifies *not determined*; it does not signify uncaused.

To primitive man simple things were obviously regular, and complex things were apparently capricious. Caprice was more impressive than monotony, and the universe was thought of as anthropomorphic. As time passed, more careful observation caused a continuous transfer of phenomena from the category of caprice to that of regularity, and the universe was accordingly interpreted as a machine, a remarkable machine controlled by its Maker, perhaps, but still a machine. Now we are to believe that the machine has broken down, and we are gravely asked to allow caprice, re-incarnated as the bastard child of the Principle of Indeterminacy, to come back and to claim to be the original source of events.

In classical mechanics, the sequence of events was determined by the initial conditions. Strictly, Heisenberg's Principle of Indeterminacy merely denies that in atomic physics this initial specification is always possible. Sommerfeld's view is that the quantum treatment concerns two discrete states, and that the final state is involved in *some* way with the initial state as a "causative" factor which cannot be "determined". This view is logically defensible. The question once was: given the initial state in all its details, what is the state that follows? The question now is: given such features of the initial state as are obtainable, and given a general knowledge of its possible final states, what is the probability of the transition from the initial state into one of those final states?

The future metaphysical interpretation of causality seems likely to be affected by the probability factors that occur in the phenomena of atomic physics as much as our view of space and time is affected by Einstein's investigation of simultaneity.

§4. Indeterminacy and Free Will

The suggested do-as-you-like methods supposed, by certain physicists, to be capriciously and spontaneously used by the atoms, have been eagerly welcomed by certain well-known people in support of human "free-will". The principle of universal determinism—the principle that all human actions have been irrevocably predetermined—is repugnant to many, perhaps to most, people; but the objection to the principle, though intellectual in form, is really emotional and moral, since it expresses an instinctive and powerful dislike or fear of any disproof of human initiative, freedom, and

responsibility. It is this emotional reaction that accounts for the welcome accorded in prominent quarters to the suggestion that even atoms are free to take their physical exercises when they please—indeterminately, unpredictably, spontaneously.

Philosophers are easily able to defend the principle of the freedom of the will without calling in the support of atomic physics. The principle would indeed be in a sorry plight if it had to obtain its chief support from an atomic gymnasium. Our ignorance of the facts of atomic physics is no good reason for postulating a defect in the law of causation. Break down causation, and we are left with chance. That is wholly unsatisfactory. It may be true that the jumps of electrons cannot be predicted, that they *seem* to occur by chance. But the laws of probability apply to a multitude, not to an individual. There must be a cause for these jumps, if jumps there are. And we may feel fairly confident that the cause will some day be discovered.

In his Oxford lecture, May, 1931, and also more recently, Einstein made it clear that his ideal of physics was a scheme of laws which were essentially deterministic.

Admittedly science cannot remain bound within the limits which the seventeenth century pioneers felt bound to impose. It must move, *but it must not move backwards.*

CHAPTER XLIV

Science: Present Tendencies

§1. Less Certainty than heretofore

During the present century developments of the different branches of physical science, we have learnt to recognize more and more fully that what appear to be facts of experience cannot always be accepted at their face value; they may be only of the nature of appearance, and the reality underlying them may be easily concealed. We have also learnt that, when experience pushes into new domains, we must be prepared for new facts of an entirely different character from those of our former experience. We are

frequently encountering new phenomena, for instance high velocities, cosmic magnitudes, small-scale magnitudes. A good deal of what passes for knowledge is tinged with doubt and is often little more than opinion. There is now a greater willingness to admit that most of the results of scientific investigation are, by a more searching analysis, subject to correction.

We should always bear in mind that all results of measurement are necessarily only approximate. In fact, all experience seems to be of this character. We never have perfectly clean-cut knowledge of anything. Our knowledge always seems to be surrounded by a zone of twilight, a shadow of uncertainty, into which we have not yet penetrated. One general consequence of the approximate character of all measurements is that no exact statements about experimental science can ever be made.

§2. The Surrender of Old Prejudices

It is still true that nothing can be more fatal to progress in science than a too confident reliance on mathematical symbols. Beginners in particular are apt to accept a formula as the physical reality. Yet a great deal in Relativity and in Quantum Physics is essentially mathematical. Physicists agree, however, that the mathematics, though probably correct, has still to be interpreted. The greatest triumph of modern physics was achieved by Maxwell in his magnetic field equations. These were the outcome of considerations of Faraday's work at the Royal Institution. It is certain that these equations have not even yet given up all the inner secrets of the physics they stand for. The mathematics of physics is not always the last word; it is often just the first step on the highroad of real discovery.

On the whole, the present tendency of scientific thought is against explanations of a purely mechanical type. It is now recognized as a rather eccentric tendency of Kelvin that he would not accept any scientific hypothesis that could not be represented by a mechanical model. The construction of models of such a thing as the atom is of necessity work of an almost wildly speculative character. All the mathematical developments of quantum mechanics *may* turn out to be based on unacceptable data, but they are certainly more trustworthy than the astronomical models of the atom. Another prejudice it behoves us to give up is our

unwillingness to concede the possibility of action at a distance, a prejudice due entirely to a longing for mechanical explanations.

There is an unfortunate tendency on the part of a certain number of prominent men of science to allow their scientific data to become deeply tinged with emotional prepossessions. We cannot, of course, be blind to the emotional side of life, or to the natural tendency of our intelligence to be led astray by our wishes. Science is, however, exclusively interested in the relations between the data of observation and experiment; it is contemplative of the order displayed, and this contemplation is entirely cold and unemotional. As for indeterminacy, we must look upon that as something provisional, something to be superseded some day. Indeterminacy is a treacherous guide to the deep seas of philosophy and will infallibly lead the unwary into the shallows.

§3. The Function of Scientific Hypotheses

An acceptable scientific hypothesis must, in addition to covering a set of well-established facts, also have certain logical characteristics to recommend it. It must not only represent the sum-total of the facts in question but it must be in a form which is logically elegant and otherwise suggestive. To be successful an hypothesis must go beyond the facts it is designed to explain and must point the way to new advances. It must give a lead to observation and experiment.

In the light of new facts most hypotheses are destined to be superseded. But an hypothesis does not usually fail because on some special point an *experimentum crucis* gives decisive proof convincing to any rational mind that it is no longer defensible. It loses its adherence because it has grown artificial and unadaptable. Copernicus did not give a mathematical proof that the Ptolemaic hypothesis of the solar system was incorrect; he only showed that a much simpler hypothesis was possible. The older system was for a long time still preferred by an astronomer of the rank of Tycho Brahe; it was never really "disproved", it simply *collapsed,* because when weighed by an increasing number of experts it was found much less satisfactory than the newer hypothesis, though none of the experts could have given an absolutely rigorous proof of its impossibility. We are all apt to talk about those hypotheses with which we have long been familiar as if they were experimentally established *facts*; most of us, for instance, think of the atom as a

real thing that could be seen, were our visual powers good enough. The existence of the atom is hypothetical; all our knowledge about it is entirely inferential; its discrete and concrete existence has certainly never been finally demonstrated. Even now proof may come along some day that atoms do not exist, though the degree of probability against this is fairly high.

The break-up of the classical physics of the nineteenth century may be ascribed to (1) the discovery of radio-activity; (2) the negative result of the Michelson-Morley experiment and Einstein's subsequent theory of Relativity; (3) the Quantum theory. To these things the best-known physicists of the world have been devoting unremitting attention for nearly a generation, and there is still no sign of finality and very little of settled opinion. No second Newton has yet appeared, and the new *Principia* has still to be born.

The solid work of men devoted to science is done in the field and in the laboratory, but a few of them nowadays spend too much of their time in painting pictures, pictures of nature not as they have learnt to know her, but of nature as they would imagine she would look *if* they knew her.

The golden rule that no concept shall be admitted into an hypothesis that has not been experimentally verified at least to the same degree of accuracy as the experiments themselves to be explained, should as far as possible be scrupulously observed. Let it be granted, however, that in practice it is not always possible to fulfil this requirement. In the investigation of the structure of the atom, for instance, we seem bound occasionally to introduce concepts without making any serious attempt to justify them. That way lies inevitable danger, though we seem to have no alternative. This, however, is a very different thing from inventing, it may be, a detailed picture of an unimaginably minute planetary system, or, perhaps, an equally detailed and highly coloured picture of an unimaginably vast universe, each on the basis of the flimsiest experimental evidence, and even some of that open to question. The ingenuity we may justly admire; the folly we are bound to condemn. Let us get our facts from laboratory and field, correlate them, and be satisfied.

Most of the new hypotheses have been given a mathematical setting. This often seems to be the only way, for some of them are built up from concepts which cannot be explained in terms of things

previously known, and therefore cannot be explained adequately in words at all. Like such fundamental concepts as proximity and identity, which everybody gradually acquires in very early childhood, the newer concepts of physics can be mastered only by long familiarity with their properties and uses. The advances that are being made are highly technical, and only men of quite exceptional logical vision, who are also exceptionally equipped mathematically, are likely to consider the newer physics to come within the four corners of what is sometimes called common sense.

Some of our old ideas we feel bound to revise in the light of new knowledge. The electric field is an instance. An examination of the operation by which we determine an electric field at any point will show that the field is something we have *constructed,* and is not a datum of experience. At the given point in the field we place an exploring charge, measure the force shown, and calculate the ratio of the force to the charge. By varying the exploring charge and by repeating the experiment many times, we may map out the field as minutely as we please, each point explored being labelled with the appropriate number and direction. The mathematician then steps in, and formulates the necessary equation. The physicist is not, however, usually satisfied with this equation; he believes that the field has a physical reality, that at every point of the field there is some physical happening which is connected, in a way not yet precisely determined, with the number and direction which label the point. Hitherto the natural corollary to this argument has been that a *medium* must exist, but now it is the fashion to say that there is no medium, and that only the "field" is real. The concept of the field as a *working tool* for correlating and predicting the properties of electrical systems seems to be fundamentally necessary, but is the experimental evidence sufficient to warrant our ascribing a physical reality to the field? Logically we are not justified in treating the concept as more than just a working hypothesis.

§4. Dogmatism in Biology still survives

The aggressive dogmatism prevalent in science half a century ago has almost faded away, though we have with us a few cosmological speculators whose universes go on expanding "for ever",

giving no thought to the fate of expanding soap-bubbles;[1] and a few stalwarts in biology are still a little contemptuous of those who question their rather pontifical judgments.

The mechanistic conception of life applies to the study of the living organism just those methods of investigation that have successfully been applied to the study of inorganic things, so that biology, or at any rate physiology, has always been the mechanics, physics, and chemistry of the period—though always a little behind the times, so to speak—applied to the investigation of functioning and behaviour.

The Cartesian mechanism of life showed us an animal automaton —a thing of hydrostatic pressure, flow of liquids through tubes of varying calibre, stretched nerve-threads actuating valves, filters and sieves, liquids that were thin and mobile or thick and viscous, liquids expansible by heat, liquids that distended hollow organs, all in accordance with the physical ideas current at that time. It reminds us of the card-playing automaton invented by Maskelyne the famous conjurer, exhibited at the Egyptian Hall half a century ago.

Then came the microscope and the minute examination of the tissues of the animal body: this was in the eighteenth century. And about the same time the earlier chemistry was applied to the study of life, and organic functioning seemed to be largely an affair of fermentations. Towards the end of this century, the true theory of combustion was worked out, and immediately the processes of animal respiration were seen to be those of oxidation, with an output of carbon dioxide. The inference seemed obvious that the body of the warm-blooded animal was analogous to an ordinary heat engine.

The first half of the nineteenth century was the classical period of physiology. The experimental investigation of the body of the mammal was carried out by methods largely physical, and still in use in the medical schools: the use of the microscope, the induction

[1] See Sir Arthur Eddington's address to the Mathematical Association, January, 1931. Doubtless Sir Arthur contemplates an infinite void, in which the universe can go on expanding "for ever". The remark in the text above implies no sort of disrespect to such eminent men as Eddington, Jeans, De Sitter, and Le Maître. The mathematical schemes they have worked out command very great respect, but the mathematics involved in the different schemes for an expanding universe is based, primarily, on a single experimental fact—that the spectra of the distant nebulæ show, in general, a shifting towards the red, most of the collateral and supporting evidence being merely inferential. But suppose it is some day discovered that the interpretation of the shift is wrong, as with further knowledge is quite possible. What about the soap-bubble, then?

coil, the galvanometer, clockwork drums for obtaining graphic records of motions of parts of the body under stimulation, the injection of blood-vessels, the stimulation of nerves, and so forth.

At the same time, chemical methods also advanced rapidly. The three main landmarks are: the first synthesis of an organic compound, the conception of colloid structure, and the notion of catalysis. Colloids dominate physiology still. Catalysis gave a new cue to physiology, so that ever since 1878, when Kuhne introduced the term "enzyme" as meaning much the same thing as the old ferment, life has been an affair of enzymes, zymogens, kinoses, anti-enzymes, hormones, vitamins, &c. The multiplicity of these substances, not one of which has been chemically isolated, much less synthesized, suggests that the fertility of physiological hypotheses is beginning to fail. We are, however, enabled to see clearly how intimately the mechanistic conception of life has been concerned with the advances made by chemists and physicists.

All that we have surveyed above represents, not biology, but rather the application of physics and chemistry to the study of the *modes of activity* of the living organism, but the last sixty years have seen the development of a biology with its own individuality and methods. A new impetus was given to biology by the initiation of experimental embryology, the modern study of cell anatomy, the investigation of the germ-plasm (the hypothetical substance of heredity), experimental breeding, and genetics. For a new conception of life, the significance of these things cannot be overestimated. No less profound has been the experimental work of Sherrington on nervous activity and its integrative function in animal life. Here we have the indispensable data of animal behaviour. The investigation of the behaviour of the intact living organism, carried out by ordinary observation, supplemented by the experimental methods just referred to, is obviously the great fertile field of biological investigation in the near future. For the present, biochemistry is taking a subordinate place.

The mechanist asserts that the results already obtained enable him to explain organic activity, to explain life itself. But if by explanation he means, as presumably he does, a redescribing of the phenomena in terms of the irreducibly simple concepts of mathematical physics, is his assertion justified?

Enzymes are said to provide the mechanism of the processes of digestion, but we are still ignorant of the physical and chemical

behaviour of any one of those agents. The coagulation of the blood has been described in terms of chemical "interactions of colloids under the influence of electrolytes, especially calcium"; thus fibrinogen passes into fibrin, prothrombin into thrombin, prothrombokinase into thrombokinase, but not one of these substances is known in the way that we know water or hydrochloric acid. The development of the organs of the body is due, it is said, to groups of developmental "factors" in the chromatoplasm of the nuclei of the germ-cells, but we do not know what is the chemical constitution of those "factors". And so on. One organic mechanism is explained by another organic mechanism, which is generally just as complex. We are bidden to see in the organism a "vista of exquisite mechanisms", apparently automata guaranteed at birth to "go" by winding one another up for three score years and ten. Such an "explanation" may satisfy a biologist, but the physicist is always a little suspicious of a machine guaranteed to maintain perpetual motion.

The vitalist insists that the living organism is something more than the mechanist's physico-chemical machine; that the kind of correlation needed for all the facts of biology involves concepts of an entirely different order from the kind of correlation needed for the facts of physics and chemistry. But when he in turn provides the organism with a causal agent that he claims to *know*, his position is as untenable as that of the mechanist. That a causal agent must be put forward hypothetically may be admitted; that anything at all is known about it must be denied.

On the other hand, biological research is likely to remain mechanistic. If a *physical* explanation of life is sought, what other line of research is possible? The logician's quarrel with the biologist is that the latter claims to *know*. He does not know.

Some biologists accept the Bergson–Alexander–Lloyd Morgan hypothesis that life, consciousness, and intelligence may have "emerged" as evolutionary factors from an earlier and cruder mechanism. Other biologists demur.

Present-day biological research is being carried out in accordance with all the accepted principles of scientific method. The wild speculations of our few biological dogmatists may be ignored.

§5. "Explanations" in Science

What is the nature of scientific *explanation*? The essence of an explanation seems to consist in reducing a phenomenon to elements with which we are so familiar that we accept them as a matter of course, and our curiosity then comes to rest. We try to redescribe the phenomena in the simplest manner possible, that is, in terms of space, time, gravitation, energy transformations, chemical constitution, and so forth. Thus, scientific explanation is obviously a relative affair, relative to the elements or axioms to which we make reduction and which we accept as ultimate. Formally, there is no limit to the process of explanation, because we can always ask what is the explanation of the elements in terms of which we have given the last explanation. It has often been emphasized that Einstein's general theory of Relativity does not *explain* gravitational phenomena, or even attempt to do so; it merely describes and correlates the phenomena in mathematical language. No more attempt is made to reduce to simple terms the gravitational attraction between the earth and the sun than was made by Newton. All our explanations are necessarily given in terms of experience. If we try to give an explanation in terms different in character from that of experience, the attempt necessarily fails, and the difficulty of giving an adequate explanation to quantum phenomena is partly due to the virtual impossibility of reducing the phenomena to elements that are familiar in old experience. The essence of the explanatory process is such that we must be prepared to accept as an ultimate for our explanations the mere statement of a correlation between phenomena or situations with which we are sufficiently familiar. If there is no other experiment suggesting other and intermediate phenomena, we have to rest intellectually satisfied with the correlation affected.

CHAPTER XLV

Philosophy and Science

§1. Philosophy and Science both Speculative

Descartes' separation of mind from matter was so far fruitful that it led to the distribution of the work to be done amongst different thinkers. The question of the nature of the mind thus gradually ceased to interest the scientific world, and philosophers gradually ceased to take much interest in science.

There is this much in common between philosophy and theoretical science: both are speculative. In both cases the views to which we are led are those which appear to us to be most intelligible. On the other hand, very little can be done in the direction of putting to a crucial test rival hypotheses in philosophy, whereas in theoretical science this is often possible and final.

The different branches of physical science are each concerned with its own set of special problems, but all are based, ultimately, on observation and experiment. Philosophy takes its place in the realm of conjecture, and its existence is justified so long as there are matters in which it is more important for us to have provisional conclusions than to have none at all. The philosopher often seems to be romancing, that is, he does not seem to be seriously engaged in the pursuit of truth. Even Einstein says that philosophers are children who play with words. And these are days when men of science sometimes yield to the very same weakness. The true business of philosophy is to subject to a critical analysis all the presuppositions of science, to synthesize scientific knowledge, and to solve the many problems which arise in the making of such a synthesis.

The discoveries of science during the last thirty or forty years have overthrown more than one philosophic system that a generation ago seemed unshakable. We need a new philosophy which shall embrace the new knowledge as well as the old. This, however, is a very serious demand. To be successful nowadays, a philosopher must be a sound mathematician, he must be master of the whole subject of logic, and he must know a great deal, and know it well, about natural science in all its branches. He should challenge every-

thing in science and mathematics that is challengeable; he should be ready to ask critical questions, to point out dark places, to pounce on inconsistencies. But he should supply constructive proposals, too.

Happily there have been signs for some years of an entente between philosophy and science. There are now comparatively few extreme men, either on the side of materialism or on the side of idealism. Mechanical and idealistic conceptions have been a good deal discredited by recent developments in physical science; biology is no longer so confident as it once was over the adequacy of natural selection, and Hegelianism is now but the shadow of a shade of its former robust self.

§2. The Proper Function of Philosophy

It has been well said that the primary function of philosophy is not, as it is the business of science, that of discovering depersonalized universal truth, but of expressing concrete personal attitudes. We expect philosophers to differ, and we do not expect them to convince one another. Many philosophers have thought that if their colleagues would be acute and intelligent, they would give up their false positions and come over to the only one that seemed defensible—their own. This attitude is quite forgivable. The more individual the man, the more individual his philosophy. Every man must have an attitude to the universe if he is to think rationally and completely, and philosophically this attitude is more comparable with the personal vision of the artist than the depersonalized vision of the man of science.

Different and quite independent systems of geometry can be built up consistently, each resting on and rigorously developed from its own special set of axioms. Philosophy presents an analogous case. More than one self-consistent system is possible because more than one set of axioms which are not self-contradictory is possible. The scientific value of a philosophic system will depend on the consistency of its reasoning and the breadth of its experience which it can cover, starting from its own axiomatic presuppositions. If the system is built up by a competent logician, the only part of it open to serious attack is the set of presuppositions, and if these are truly representative of the philosopher's deepest experience in which his certainty in life is based, the system *for him* is true.

The present Master of Balliol, Mr. A. D. Lindsay, tells this story: "I remember how, when I was an undergraduate at Oxford, Balliol men who were reading philosophy with Caird would, in imitation, sometimes conscious and sometimes unconscious, of the master, consign a philosopher to outer darkness with the fatal words, 'He's a Dualist'." The world has moved since then.

It is a just criticism of modern philosophy that each worker has been content to make each his own contribution, perhaps a new "system", without any reference to a general idea of building up knowledge as a whole. It is for this reason that philosophy, apart from logic, has remained in so unprogressive a state. The ancient philosophers certainly did try to deal with the greater problem, but in those days an intelligent man could, with comparative ease, make all knowledge his province.

Will science in the future obtain from philosophy the critical help it so much needs? Or will philosophy find the task too great?

§3. Modernist Tendencies

With the names of such men as Epstein representing sculpture, Matisse representing painting, and Stavinski representing music, critics of the "modernist" movement have coupled the names of such thinkers as Croce representing philosophy, Bertrand Russell representing mathematics, and Schrödinger representing science, the critics maintaining that all such representative men of the modern schools of thought would be utterly unintelligible to men of the classical schools, represented by, for instance, Phidias, Rembrandt, Beethoven, Aristotle, Newton, and Faraday, respectively; unintelligible because they use a set of logical categories entirely different from the classical categories, and therefore talk a language which divides us completely from the mentality of the past.

"The changes in our mentality have been hailed as a triumph of open-mindedness, of the abandonment of all our prejudices, of the unstiffening of our theories." "This contempt of our native mentality pervades our entire culture." "There is a certain wantonness in present-day thought. When we are brought to the brink of the unreasoning, there is something radically wrong in the thinking that brought us there." "Even in science there is too great a willingness to combine incompatibles, and to make a show of some respect for the irrational. In physics we have reached a

point which is dangerously close to the unmeaning. A perversity which sacrifices intelligibility to unverified 'facts' suggests a mentality at once unscientific, illogical, and unphilosophical."

These criticisms of science are certainly not without justification, though they are perhaps a little too severe. Students of scientific method should allow nothing to shake their faith in the methods of Newton and Faraday. The leading representatives of the different schools of modernist thought are admittedly distinguished men, but their methods should not be followed by beginners.

Books for Reference

1. *Atomic Physics.* Max Born. (Now the leading book on the subject.)

2. *The Endless Quest.* F. W. Westaway.

3. *The New Chemistry.* E. N. da C. Andrade.

4. *Relativity, Gravitation, and World Structure.* E. A. Milne.

5. *Atomic Structure and Spectral Lines.* Arnold Sommerfeld.

6. *The Wave Mechanics and Free Electrons.* G. P. Thomson.

7. *Quantum Chemistry.* A. Haas.

8. *Die physikalischen Prinzipien der Quantentheorie.* W. Heisenberg. (There is an American translation.)

9. *La Théorie des Quanta. Les Statiques Quantiques et leurs applications.* L. Brillouin.

10. *Selected Papers on Wave Mechanics.* De Broglie and Brillouin.

11. *Collected Papers on Wave Mechanics.* E. Schrödinger.

12. *An Outline of Wave Mechanics.* N. F. Mott.

13. *The Principles of Quantum Mechanics.* P. A. M. Dirac.

14. *Critique of Physics.* L. L. Whyte.

15. *The Logic of Modern Physics.* P. W. Bridgman.

16. *Scientific Inference.* Harold Jeffreys.

17. *Science and First Principles.* F. S. C. Northrop.

18. *The Nature and Scope of Physical Science.* H. Dingle.

19. *Leçons sur les ensembles analytiques et leurs applications.* N. Lusin. (Deals largely with the borderline between mathematics and philosophy.)

BOOK V

SOME DISTINGUISHED WORKERS OF THE PRESENT DAY

CHAPTER XLVI

1. Mr. Bertrand Russell

Scientific Method aims at Objective Certainty

Mr. Bertrand Russell (as Earl Russell still prefers to be called) is an eminent mathematician, whose various works on the philosophy of mathematics are held in esteem all over the world. Unconventional in outlook, a master of lucid exposition, he is always interesting, though his way of putting things is sometimes apt to give a little shock to Victorian ears. His *Scientific Outlook*, from which we quote, is largely concerned with scientific technique.

(1) From Chapter I, *Examples of Scientific Method*, § 3: DARWIN as an exemplar:

"The earliest triumphs of scientific method were in astronomy. Its most noteworthy triumphs in quite recent times have been in atomic physics. Both these are matters requiring much mathematics for their treatment. Perhaps in its ultimate perfection all science will be mathematical, but in the meantime there are vast fields to which mathematics is scarcely applicable, and among these are to be found some of the most important achievements of modern science.

"We may take Darwin's work as illustrative of the non-mathematical sciences. Darwin, like Newton, dominated the intellectual outlook of an epoch, not only among men of science, but among the general educated public; and, like Galileo, he came into conflict with theology, though with results less disastrous to himself. Darwin's importance in the history of culture is very great, but the value of his work from a strictly scientific point of view is difficult to appraise. He did not invent the hypothesis of evolution, which had occurred to many of his predecessors. He brought a mass of

evidence in its favour, and he invented a certain mechanism which he called 'natural selection' to account for it. Much of his evidence remains valid, but 'natural selection' is less in favour amongst biologists than it used to be.

"He was a man who travelled widely, observed intelligently, and reflected patiently. Few men of his eminence have had less of the quality called brilliance; no one thought much of him in his youth. At Cambridge he was content to do no work and take a pass degree. Not being able, at that time, to study biology in the university, he preferred to spend his time walking round the country collecting beetles, which was officially a form of idleness. His real education he owed to the voyage of the *Beagle*, which gave him the opportunity of studying the flora and fauna of many regions, and of observing the habitats of allied, but geographically separated, species. Some of his best work was concerned with what is now called ecology, i.e. the geographical distribution of species and genera. He observed, for example, that the vegetation of the High Alps resembles that of the Polar regions, from which he inferred a common ancestry at the time of the glacial epoch.

"Apart from scientific details, Darwin's importance lies in the fact that he caused biologists, and through them, the general public, to abandon the former belief in the immutability of species, and to accept the view that all different kinds of animals have been developed by variation out of a common ancestry. Like every other innovator of modern times, he had to combat the authority of Aristotle. Aristotle, it should be said, has been one of the great misfortunes of the human race. To this day the teaching of logic in most universities is full of nonsense for which he is responsible.

"The theory of biologists before Darwin was that there is laid up in Heaven an ideal cat and an ideal dog, and so on; and that actual cats and dogs are more or less imperfect copies of these celestial types. Each species corresponds to a different idea in the Divine Mind, and therefore there could be no transition from one species to another, since each species resulted from a separate act of creation. Geological evidence made this view increasingly difficult to maintain, since the ancestors of existing widely separated types were found to resemble each other much more closely than do the species of the present day. The horse, for example, once had his proper complement of toes; early birds were scarcely distinguishable from reptiles, and so on. While the particular mechanism of "natural

selection" is no longer regarded by biologists as adequate, the general fact of evolution is now universally admitted among educated people.

"In regard to animals other than man, the theory of evolution might have been admitted by some people without too great a struggle, but in the popular mind Darwinism became identified with the hypothesis that men are descended from monkeys. This was painful to our human conceit, almost as painful as the Copernican doctrine that the earth is not the centre of the universe. Traditional theology, as is natural, has always been flattering to the human species; if it had been invented by monkeys or inhabitants of Venus, it would, no doubt, not have had this quality. As it is, people have always been able to defend their self-esteem, under the impression that they were defending religion. Moreover, we know that men have souls, whereas monkeys have none. If men developed gradually out of monkeys, at what moment did they acquire a soul? This problem is not really any worse than the problem as to the particular stage at which the fœtus acquires a soul, but new difficulties always seem worse than old ones, since the old ones lose their sting by familiarity. If, to escape from the difficulty, we decide that monkeys have souls, we shall be driven, step by step, to the view that protozoa have souls, and if we are going to deny souls to protozoa, we shall, if we are evolutionists, be almost compelled to deny them to men. All these difficulties were at once apparent to the opponents of Darwin, and it is surprising that the opposition to him was not even more fierce than it was.

"Darwin's work, even though it may require correction on many points, nevertheless affords an example of what is essential in scientific method, namely, the substitution of general laws based on evidence for fairy tales embodying a fantasy of wish-fulfilment. Human beings find it difficult in all spheres to base their opinions upon evidence rather than upon their hopes. When their neighbours are accused of lapses from virtue, people find it almost impossible to wait for the accusation to be verified before believing it. When they embark upon a war, both sides believe that they are sure of victory. When a man puts his money on a horse, he feels sure that it will win. When he contemplates himself, he is convinced that he is a fine fellow who has an immortal soul. The objective evidence for each and all of these propositions may be of the slightest but our wishes produce an almost irresistible tendency to believe.

Scientific method sweeps aside our wishes and endeavours to arrive at opinions in which wishes play no part. There are, of course, practical advantages in the scientific method; if this were not so, it would never have been able to make its way against the world of fantasy. The bookmaker is scientific and grows rich, whereas the ordinary betting man is unscientific and grows poor. And so in regard to human excellence, the belief that men have souls has produced a certain technique for the purpose of improving mankind, which, in spite of prolonged and expensive effort, has hitherto had no visible good result. The scientific study of life and of the human body and mind, on the contrary, is likely, before very long, to give us the power of producing improvements beyond our previous dreams, in the health, intelligence, and virtue of average human beings.

"Darwin was mistaken as to the laws of heredity, which have been completely transformed by the Mendelian theory. He had also no theory as to the origin of variations, and he believed them to be much smaller and more gradual than they have been found to be in certain circumstances. On these points modern biologists have advanced far beyond him, but they would not have reached the point at which they are but for the impetus given by his work; and the massiveness of his researches was necessary in order to impress men with the importance and inevitability of the theory of evolution."

(2) From Chapter II, *Characteristics of Scientific Method:*

"All exact science is dominated by the idea of approximation. When a man tells you that he knows the exact truth about anything, you are safe in inferring that he is an inexact man. Every careful measurement in science is always given with the probable error, which is a technical term, conveying a precise meaning. It means: that amount of error which is just as likely to be greater than the actual error as to be less. It is characteristic of those matters in which something is known with exceptional accuracy that, in them, every observer admits that he is likely to be wrong, and knows about how much wrong he is likely to be. In matters where the truth is not ascertainable, no one admits that there is the slightest possibility of even the minutest error in his opinions. Who ever heard of a theologian prefacing his creed, or a politician concluding

It is an odd fact that subjective certainty is inversely proportional to objective certainty. The less reason a man has to suppose himself in the right, the more vehemently he asserts that there is no doubt whatever that he is exactly right. It is a practice of theologians to laugh at science because it changes. 'Look at us,' they say. 'What we asserted at the Council of Nicea we still assert; whereas what the scientists asserted only two or three years ago is already forgotten and antiquated.' Men who speak in this way have not grasped the great idea of successive approximations. No man who has the scientific temper asserts that what is now believed in science is exactly right; he asserts that it is a stage on the road towards the exact truth. When a change occurs in science, as, for example, from Newton's law of gravitation to Einstein's, what had been done is not overthrown, but is replaced by something slightly more accurate."

(3) From Chapter III, *Limitations of Scientific Method:*

"It is characteristic of the advance of science that less and less is found to be datum, and more and more is found to be inference. The inference is, of course, quite unconscious, except in those who have trained themselves to philosophical scepticism; but it must not be supposed that an unconscious inference is necessarily valid. Babies think that there is another baby on the other side of the looking-glass, and although they have not arrived at this conclusion by a logical process, it is nevertheless mistaken. Many of our unconscious inferences, which are, in fact, conditioned reflexes acquired in early infancy, are highly dubious as soon as they are subjected to logical scrutiny. Physics has been compelled by its own necessities to take account of some of these unwarrantable prejudices. The plain man thinks that matter is solid, but the physicist thinks that it is a wave of probability undulating in nothingness. To put it briefly, the matter in a place is defined as the likelihood of your seeing a ghost there. For the moment, however, I am not yet concerned with these metaphysical speculations, but with the features of scientific method which have given rise to them. The limitations of scientific method have become much more evident in recent years than they ever were before. They have become most evident in physics, which is the most advanced of the sciences, and so far

these limitations have had little effect upon the other sciences. Nevertheless, since it is the theoretical goal of every science to be absorbed in physics, we are not likely to go astray if we apply to science in general the doubts and difficulties which have become obvious in the sphere of physics.

" The limitations of scientific method may be collected under three heads: (1) the doubt as to the validity of induction; (2) the difficulty of drawing inferences from what is experienced to what is not experienced; and (3) even allowing that there can be inference to what is not experienced, the fact that such inference must be of an extremely abstract character, and gives, therefore, less information than it appears to do when ordinary language is employed."

And then follows admirable expositions of those limitations. The whole book should be mastered by every student of scientific method.

CHAPTER XLVII

2. Dr. Harold Jeffreys

Is Scientific Method now open to Suspicion? No. Quantum Theories

Dr. Harold Jeffreys, the leading geophysicist in this country, adopts as a primitive postulate in his book *Scientific Inference*, the principle that from facts definitely ascertained by the senses it is possible to make *inferences* beyond the data directly known by sensation, and that the principle leads to an explanation and a justification of the high probabilities attached in practice to simple quantitative laws. More generally, he examines the validity of certain basic aspects of scientific method.

After discussing the validity of the major premiss in the old classical syllogism " All men are mortal ",[1] Dr. Jeffreys proceeds to discuss the present position of certain scientific laws:

" At present we are faced with the inaccuracy of Euclid's parallel

[1] Cf. p. 166.

axiom, which for millennia was considered intuitively obvious; with the inaccuracy of Newton's law of gravitation, which had been well established by experience, and had been believed for centuries to be exact; with the failure in stars of the law of the indestructibility of matter; and with the discordance of the classical undulatory theory of light with the group of facts known as quantum phenomena. For twenty years physical science has been modifying and reconstructing its most fundamental laws as a result of new knowledge. The reconstruction has followed, and will continue to follow, the old *method*, but the results will be different because new facts have to be fitted in. Will modern physics suffer in turn the fate of the old? Perhaps; nobody knows. But in the circumstances we must raise a group of questions more fundamental and general than any physical law. Have recent developments shown that scientific method itself is open to suspicion, and if so, is there a better one? Just how much do we mean when we assert the truth of a scientific generalization? When we have made such a generalization, what reason have we for supposing that further instances of it will be true?

"The answers to these questions may be stated at once. There is no more ground now than thirty years ago for doubting the general validity of scientific method, and there is no adequate substitute for it. When we make a scientific generalization, we do not assert the generalization or its consequences with certainty; we assert that they have a high degree of probability on the knowledge available to us at the time, but that this probability may be modified by additional knowledge. The more facts are shown to be co-ordinated by a law, the higher the probability of that law and of further inferences from it. But we can never be entirely sure that additional knowledge will not some day show that the law is in need of modification. The law is provisional, not final; but scientific method provides its own means of assimilating new knowledge and improving its results. The notion of *probability*, which plays no part in logic, is fundamental in scientific inference. But the mere notion does not take us far. We must consider what general rules it satisfies, what probabilities are attached to propositions in particular cases, and how the theory of probability can be developed so as to derive estimates of the probabilities of propositions inferred from others and not directly known by experience.

At the same time a remarkable thing happens. It is found that

general propositions with high probabilities must have the property of mathematical or logical simplicity. This leads to a reaction upon the descriptive part of science itself. The number of possible methods of classifying sensation is colossal, perhaps infinite. But the importance of simple laws in inference leads us to concentrate on those properties of sensations that actually satisfy simple laws as far as they have been tested. Thus the classifications of sensations actually adopted in practical description are determined by considerations derived from the theory of inference; and probability, from being a despised and generally avoided subject, becomes the most fundamental and general guiding principle of the whole of science."

Dr. Jeffreys points out that in the development of knowledge our fundamental data are sensations and certain *a priori* principles of logic and probability, and that, as we proceed, we construct from them concepts of increasing generality. He asks if there is any reason to suppose that the process will ever stop, in other words, will our concepts ever become ultimate. Matter was once thought to be impenetrable, but Dalton reduced it to molecules, then the molecules were reduced to atoms, and now the atoms have been reduced to protons and electrons; these protons and electrons occupy but a tiny fraction of the whole region within the apparent outer surface. The greater part of what we call matter is simply empty space, and our knowledge of the basic particles is entirely inferential. Is this knowledge, *knowledge*?

"These modern views on the constitution of matter did not lead directly to the abandonment of the idea of a physical object as an ultimate reality, but rather to the attitude that the object, as usually understood, is composed of smaller things, which are still objects; that is, like the physical object before the time of Dalton, they have definite positions at any time, and no two of them can occupy the same region. But even this position is being assailed by the new quantum mechanics. According to Heisenberg's uncertainty principle, which is a simple consequence of any quantum theory, it is never possible to measure the position and velocity of a particle accurately at the same time; whichever of them we try to measure, the process affects the other, and an indeterminacy remains in both. Relativity has left us thinking that an event can be specified by stating exact values of four variables, three position

co-ordinates and the time. Heisenberg leaves us in doubt as to whether these variables can have any exact values at all; and if the position of a particle is indefinite it becomes doubtful whether the statement that two particles cannot be in the same position has any meaning.

In the various forms of the new quantum mechanics the four variables needed to specify the time and the position of any particle have ceased to be physical magnitudes at all; a single numerical measure is not enough to specify any one of them. In Heisenberg's theory each is replaced by a matrix, an assemblage of several magnitudes; in that of Dirac the co-ordinates and the corresponding momenta are what he calls q-numbers, which do not satisfy the ordinary rule of multiplication $pq = qp$. In the theory of Schrödinger an entirely new variable, the wave-function ψ, appears, which satisfies a certain differential equation, and the observed phenomena of electron emission, radiation, and so on emerge as expressions of the properties of the wave function. All three theories appear to give the same answers, and to be well confirmed by experiment. But all agree in that the ultimate particles do not have definite co-ordinates at any instant. The proton and the electron, as particles with definite positions, have disappeared."

"The existence of three such theories, all giving results in agreement with the facts, but formally quite different, leaves us in considerable doubt about ultimate concepts. A fruitful source of philosophical discussion is the reality of scientific concepts. So far as I can see what is usually meant by this is the existence or otherwise of atoms, electrons, light waves, and so on as ultimate realities in the same sense as physical objects appeared to be ultimate realities to the eighteenth-century physicist. The answer to this seems to be definitely in the negative; but the question is replaced by that of the reality of co-ordinates, momenta, and wave-functions. It seems to me that this question may well be postponed till we have made more progress with the various new quantum theories, particularly in the direction of co-ordinating them with the general theory of relativity. In any case the concepts that appear explicitly in the theories are quite different in character from physical objects. From the standpoint of scientific method the one and only test of the validity of concepts is whether the laws they are supposed to satisfy explain our sensations; whether this is

also a ground for attributing philosophical reality to them is a different question."

The Theory of Inference is certainly a necessary supplement to any book on scientific method.

CHAPTER XLVIII

3. Professor H. Levy

Particles or Waves? The Difficulties of Isolation

Professor H. Levy, of the Imperial College of Science, London, a distinguished mathematician and, when expounding or writing, " an inexorable logician ", is the Author of *The Universe of Science*, a book which to all students of scientific method is simply invaluable. We may quote from the preface:

" In this book I have endeavoured to sketch in broad outline the background against which the scientific movement has to be seen. By recognizing it as a feature of a developing society, we can assess the methods it has evolved to select those aspects of the changing world that are amenable to scientific analysis, the nature of the tools and instruments it has found essential in handling them, and the criteria of scientific truth. The same process shows up in relief the field within which science can at present operate with assurance, and exposes to view the tendencious idealism of contemporary expositors for many of whose pronouncements science provides no justification whatsoever. The mathematician, in particular, has become so dominant of recent years, and the field of experimental science has become so impregnated with his terminology, that Mathematical Physics, to many interpreters, has taken on the appearance almost of a separate science where facts about the world are *proved* rather than discovered by observation and experiment. As the treatment becomes more and more abstract, the symbols become the realities, and their properties when capable of being re-interpreted become evidence to these writers that there is a new mystery in the universe. The Numbers, that initially were mere measures of qualities, are divorced from their setting, and

Science usurped by Mathematics is represented as dealing only with superficial structure, and so the Universe itself eludes us."

Again:

"I make no apology for the apparently new use of the words Isolation and Isolate, where philosophers have probably used Abstraction or Exclusion."

From his very suggestive chapter headed "Unpicking the Threads", we may quote § 11, which deals with some of the difficulties which students of modern physics experience when trying to "isolate", for purposes of observation and experiment, some part of a particular physical system.

"It does not follow from this that the method of isolation will necessarily always be successful, nor, on the other hand, that if it fails there is some supernatural agency at work. Persistent failure to expose how it fails would be a serious matter. It may not be out of place to indicate here and now where it appears that this stage has been reached in connection with these little particles of negative electricity we call electrons. They, as we know, are shot off from matter in the radio-active state, so that they must be regarded as a constituent of these substances. They are never encountered in the isolated state, as individuals, although a track they have presumably traced out may be photographed on a sensitive plate, or a splash as they fall on a luminescent screen may be quite clearly distinguished. In such circumstances they behave like any particle, and therefore in themselves they may be regarded as isolated systems whose characteristics one might expect to resemble those of ordinary particles of matter, except that they are known to hold an electric charge. On this basis therefore a perfectly definite picture may be built up, that fits into the traditional scientific scheme. When they are allowed to impinge on a thin metal film, however, instead of behaving like any self-respecting old-fashioned particle, a new feature emerges. They give rise to a pattern of the type that would be produced if they were in effect the centre of a wave disturbance. Never before in the history of science has anything been encountered that may at one moment act as a discrete and isolated particle and at the next as a wave. We cannot picture it as an entirety. With the possible exception of light itself, to which it is closely related, we have not experienced its like before. Its behaviour does not

appear consistent, and consistency of behaviour is an essential for the formation of an isolated system in science. Perhaps it is not precisely correct to say that it is not consistent. In certain circumstances it does behave consistently as a charged particle and in others consistently as a wave. It has, as it were, two separate identities. In two different environments it exhibits vastly different forms of behaviour. In the terminology to which we have been objecting it would be stated that electrons have both particle and wave *properties*. To describe this, the word *wavicle* has been suggested. It is not surprising therefore to discover that science finds itself baulked in its attempt to predict precisely what will happen to such a " particle ". It can predict with great assurance what on the average will happen to a crowd of these fickle entities, but the single member evades it.

" Why is this? I do not wish here to anticipate the discussion I propose to give later on the place of prediction and determinism in science, but it is worth while noting certain points at this stage. Science, as I have stressed, is basically experimental. Whatever its theories, it never dare proceed with assurance further than experiment can penetrate. When an effort is made to form an isolate from a mass of known data it is to experiment that we must turn to supply the criterion whether the system is indeed neutral and isolated. In the case of the electron we are dealing with the smallest entity perceivable. A single specimen is not seized, held firmly, and studied in detail. They have to be taken as they are found, in exceedingly high states of motion, studied in their passage during incredibly short intervals of time. These intervals of time, as we have explained, are themselves marked off for us by portions of matter signalling events equivalent to the beating of a pendulum. The distances the experimenter has to measure, however they may be obscured, have to be separated by marks on a scale, and the very apparatus he uses contains vast numbers of the class of object —electrons—he is examining. What basis of evidence can he then have for expecting that the apparatus he uses and the individual object he desires to study, and concerning whose behaviour he desires to make predictions, separately constitute isolated systems? The very process of studying and measuring these elementary entities necessarily requires that they must be handled at such close quarters as to disturb the environment we normally presume to be neutral. This shows itself in a variety of ways, but here it is

merely necessary to mention one. We have become accustomed to regard the speed and the position of a body as two separate features of its state, two independent isolated systems, and there is good justification for it. With most objects we can study them 'at rest' within our environment where the changes in its sub-system occur so slowly in relation to the speed of our perceiving apparatus that their separation appears to be valid. We ignore the changes in the first instance and regard the object as an isolated and permanent and localized system. It may be moving, it may be at rest, but it is an *object* whatever its state of motion.

"With an electron, however, no such permanent features have ever been discovered. It is never caught 'at rest'—it flashes past at an incredible speed, its mass depends on its speed. It is doubtful whether there could be such an entity as an electron at rest. In point of fact when it strikes a metal film and becomes *at rest*, it shows itself as a system of waves, it vanishes as a particle. Here, then, at this level of smallness, position, speed, and mass are not necessarily separable, and we begin to recognize that the permanently isolated systems, object, position, and speed are no longer separately neutral. If we seize on one and insist on regarding such qualities as independent and unchanging, we do so at peril to the others we have ignored. What will happen then if we endeavour to specify accurately the 'position' of the electronic 'particle' as it is moving? We are likely to find that the more accurate the specification is attempted, the less accurately will we be able to specify its speed. When the speed is the highest possible—the velocity of light, the particle is everywhere. When the speed is zero, the position of the particle cannot be stated. It is no longer a particle. We must not be surprised if, between these two extremes, the theoretical isolate we insist on retaining behaves rather peculiarly."

Thus we have "indeterminacy", as modern physics calls it.—The chapter on "Scientific Determinism" is particularly illuminating.

CHAPTER XLIX

4. Professor Émile Borel

Relativity: An Inclusive Synthesis of Earlier Syntheses. Experiment still the Sovereign Judge

Professor Émile Borel, one of the most distinguished of living French mathematicians, is the author of *Space and Time*. The book sets out to be a semi-popular description of the Theory of Relativity, but really it is more than that, for it is a complete account of the Theory, so far as an account can be made complete without the use of serious mathematical terminology. Professor Borel's *method* is to show how the theory is just an inevitable synthesis of a number of lesser and earlier syntheses, and he explains in masterly fashion not only the theory itself but its several contributing factors. To appreciate the method fully, the whole book must be read. We can afford space only for three short extracts:

(1) From the *Introduction*:

"Thus, at the beginning of the twentieth century, universal gravitation presented itself as one of the best founded of scientific doctrines, established with almost absolute accuracy. There were, of course, some astronomical phenomena, the most important being the secular motion of the perihelion of Mercury, which did not absolutely agree with the predictions of theory, but the differences were extremely small. Besides, during the nineteenth century it had been noticed on several occasions that a more minute analysis and improved means of observation resulted in reducing similar differences to zero, so that the hope was still entertained that the law might be kept intact at the price of only an infinitesimal touching up.

"There was, however, something rather strange in this phenomenon of gravitation, something that distinguished it from other physical phenomena. This was its utter immutability and its absolute independence of all external actions. Light is arrested by opaque bodies, deviated by prisms and lenses; electrical and

magnetic actions are modified by the neighbourhood of certain bodies; gravitation alone remains always the same, and we have no means enabling us either to increase or to diminish it. Gravitation is indifferent to all physical circumstances and is not affected by the chemical nature of bodies. Radio-activity alone has furnished us with an analogous example of a property which is equally invariable, but this property, it must be remembered, is that possessed by a particular kind of matter, whilst the law of gravitation holds good for all matter. We must, however, call attention to the fact that, quite recently, the Italian savant Majorana has obtained certain results with regard to the absorption of gravitation by intervening bodies. These results, if confirmed, will be of far-reaching importance, but for the present the number of experiments is too small to be taken into consideration here.

"Thus gravitation occupied among scientific laws a prominent but isolated place, having no connection with the other laws. It had its particular domain where it reigned supreme, without fear of any possible interference, but it remained outside the constantly increasing close relationships established between the various parts of science. Many people are of opinion that these close relationships existing between the numerous scientific disciplines, even if they are not the whole of science, are at least its grandest expression. If the only worthy aim of human activity is the conquest of truth, we can hope to come near this inaccessible goal only by means of constantly widening syntheses. It is because it has effected the entry of universal gravitation into a more general conception of the world, particularly connecting it with electrical and luminous phenomena, that Einstein's theory of general relativity has been received with such admiration and passionate curiosity in scientific circles all over the world. We know that it was the Royal Society of London which, in 1918, took the initiative in organizing astronomical expeditions, the result of which was that the observation of the solar eclipse on 29th May, 1919, furnished us with a striking verification of the predictions which had been made on the strength of Einstein's theory. Newton's fame has nothing to fear from a progress which drags his law forth from its splendid seclusion and confers upon it a more lively rôle in the arena of scientific activity."

(2) *Einstein's purely Geometrical Representation:*

"Every physical phenomenon takes place at a definite moment and at a definite place. We shall not discuss the difficulties involved in the measurement of time and space, although Einstein's solution of these difficulties is fundamental. We shall obtain a first description of the phenomena if we possess a complete knowledge of the totality of the numerical data which enable us to locate them in space and in time. But this description of the phenomena will, we can see, be incomplete, since it is not sufficient to know only where and when an event happens; we must also know what is happening; whether it is, for instance, a question of the displacement of a material body, of an electrical current, or of a solar ray. So far as a complicated mathematical theory can be expressed in ordinary language at all, we might sum up Einstein's theory by saying that a full and complete knowledge of space and time relations is sufficient for a description of the universe. The nature of phenomena, and in particular the localization of matter and electricity, are deduced by means of simple formulæ from these relations of space and time. We have thus attained the highest degree of simplicity which, as it seems, we have any right to hope for, since all the numerical data refer to measurements of the same nature; the quality of the phenomena is entirely reduced to their quantity. The measurements of space and the measurements of time may be considered as being of the same nature; we know, in fact, that an interval of time is measured by the space traversed by light during that interval. The unity thus established does not, of course, get over the fact that a detailed analytical description is not necessarily the most perfect description of phenomena. Two hundred thousand accounts such as those given by Fabrice[1] would not constitute the best story of the battle of Waterloo; and, similarly, a detailed account, supposing such a thing to be possible, of the history of the milliards of milliards of molecules in a grain of corn would not be a substitute for a good description of germination. By the side of the general theory there will always exist particular theories, probably becoming more and more numerous as time goes on, but the variety and complexity of these additions should not prevent us from recognizing the importance of the simple basic theory, the scientific interest of which is not less than the philosophical. The trees must not prevent

[1] The hero of Stendhal's *Chartreuse de Parme.*

us from seeing the wood, but neither should we ignore the fact that the wood consists of trees, the trees of cells, the cells of atoms, and the atoms of corpuscles in motion."

(3) *The Detractors of the Theory of Relativity*:

"We must not expect, however, the systematic detractors of the theory of relativity to disarm at once. A curious consequence of the celebrity so rapidly attained by this theory was the attention bestowed upon it by a number of people who are not usually in the habit of taking an interest in mathematical and physical speculations. Popular articles published in reviews and even in daily newspapers have given these people a frequently wrong and always incomplete idea of the theory of relativity. Moreover, the efforts, often laudable, made by the popularizers to render the theory comprehensive have had the result of persuading many people that they have mastered all the details of the theory, whilst in reality they have at the utmost acquired only a general outline.

"Hence arose the idea that a theory which could be explained in the few pages of a review article or in a column of a daily paper could also be criticized or refuted in an article of the same length.

"Those who have undertaken the task of refuting the theory do not realize that behind the review articles, simple résumés of the theory, there exist a vast number of studies, published either in special journals or as separate works, and that those innumerable purely technical studies constitute a coherent mass which it is very difficult to shake or unsettle. It is not by discussing the terms of a review article, or even of a small work like the present, that one can hope to demolish a theory the essentials of which can only be explained with the help of numerous developments and innumerable mathematical formulæ.

"Those who are anxious to refute or even to discuss the theory of relativity should first take the trouble to study it thoroughly, but only very few people have taken this trouble. Mathematicians and physicists whose previous training and studies put them in a position to make such a deep and thorough investigation and who had at first been somewhat sceptical with regard to the new theories, have now adopted a more prudent attitude and have ceased to write on the subject of the theory of relativity.

"We must therefore warn the public against these ostensibly

scientific publications which are only the simple results of the author's imagination and are in no way based upon any serious foundation, failing as they do to take account of the vast number of studies on the theory published during the last few years.

"In addition to these apparently scientific refutations of the theory of relativity, we must also mention the very numerous philosophical studies to which the theory of relativity has given rise or for which it has served as a pretext.

"It would appear that the majority of these philosophical studies are based on a sort of play upon words. The term "relativity" has for a long time been employed by the philosophers with a more or less precise meaning. Speaking generally, the word *relative* in philosophical language is opposed to *absolute.* The term *relativity* is used by Einstein and the physicists in an undoubtedly legitimate but nevertheless special sense.

"Scientific language is necessarily much more precise than philosophical and popular language, so that scientists are compelled either to invent entirely new words or to borrow words from ordinary language, defining the precise sense in which they are to be used. It is thus that the term *function* has for mathematicians a very narrow sense, differing from the various senses it possesses in ordinary language.

"Such is also the case with regard to the word relativity, which one should avoid employing except with the addition of the epithets *special* or *general.* These expressions denote physical and mathematical theories, and it is really an abuse of language to endeavour to interpret them while sticking to the ordinary meaning of the term relativity.

"Apart from this, we see nothing to regret in the fact that the popularity of Einstein's theory has led the philosophical public to reflect upon relativity in general, and it is quite possible that this reflection has resulted in interesting results. This, however, is a simple verbal coincidence, and these results are entirely outside our subject.

"If one conclusion rather than another is to be drawn from the present work it is that of the experimental character of the new conception of space and time to which the theory of relativity leads. We are very willing to believe that we have the intuition of some sort of universal time, and it is the existence of this feeling of intuition which is the cause of the instinctive repulsion experienced

by those who are faced for the first time by the new theories. A little reflection, however, will be sufficient to make them understand that if we talk, for example, of *the event which is taking place upon the sun at the moment whilst I am speaking*, the precise sense of the expression can be defined only by appealing to certain experiments, either real or ideal. Both the problem of time and the problem of space connected with it are thus transferred from the philosophical and theoretical to the experimental domain. This is a definite philosophical advance which it will be impossible ever to lose. But we must not lose sight of the fact that the very adoption of this point of view involves, so far as the adherents of the new theory are concerned, the strict obligation to turn to experiment as sovereign judge. They should furnish experimental proofs of the new theory. We have already indicated a certain number of such proofs, but are bound to admit that relatively their number is still limited, and that, on account of the precision they require, they are of an extremely delicate nature.

"We cannot, of course, hope to be able to demonstrate the theory of relativity by means of phenomena on a gross scale, but we are entitled to think that the developments of experimental technique will enable us to predict and to verify a greater number of phenomena accessible to all careful experimentalists. On the day on which this desideratum is realized, there will be no detractors of the theory of relativity, as there are none of Newton's cosmology."

CHAPTER L

5. Professor Herbert Dingle

Relativity is an Abstraction: the Quantum Theory is an Hypothesis

Professor Herbert Dingle, of the Imperial College of Science and Technology, is the author of *Science and Human Experience*, a book which gives an account of the great changes which have taken place in physics during recent years, and which, in its general setting,

is a philosophy of present-day scientific method. The subjects of abstraction and hypothesis are dealt with in a particularly happy way:

(1) From the *Introduction*:

"Science has almost invariably restricted itself to the familiar processes of observation and experiment (which is simply observation of what happens under prescribed conditions) for the accumulation of her data, and to abstraction and hypothesis for their rational correlation.

"Abstraction is the detection of a common quality in the characteristics of a number of diverse observations: it is the method supremely exemplified in the work of Newton and Einstein. Newton, for example, gave us 'laws of motion'. Now motion is not an experience; what we observe are moving bodies. Motion is an abstraction, a quality conceived to be possessed by all moving bodies, however much they may differ in size, shape, colour, beauty, virtue, or anything else. The laws of motion express the characteristics of this common quality, and they are therefore a rational means of correlating a vast body of common experience.

"An hypothesis serves the same purpose, but in a different way. It relates apparently diverse experiences, not by directly detecting a common quality in the experiences themselves, but by inventing a fictitious substance or process or idea, in terms of which the experiences can be expressed. An hypothesis, in brief, correlates observations by adding something to them, while abstraction achieves the same end by subtracting something."

(2) From Chapter IV, *The Extremity of Abstraction—Relativity*:

"The achievement of Einstein is to describe the natural behaviour of bodies in space-time. The laws of motion and gravitation thus become united; motions are described simply as they are, and in place of the three abstractions, space, time, and force, we have one, namely, space-time.

"It is widely imagined that absolute space and time are facts of observation, and that the space-time of relativity is something hidden in Nature, the discovery of which affords one more example that things are not what they seem. The truth is, however, that absolute space and time, like space-time, are simply abstractions

from observation. They are none of them 'facts', but space-time is preferable to absolute space and time separately because it allows the correlation of a range of facts with which the independent conceptions are powerless to deal. The abstract character of absolute space and time is easily recognizable apart from relativity altogether.

"In what way have our ideas of the nature and scope of physical science been modified by the principle of relativity? Considered in the very broadest way, the answer is: Not at all. Einstein has simply extended the sway of Newtonian principles over a region of phenomena which Newton never knew. He has started from the facts of observation and submitted his ideas to the test of further observations, by which they have been supported. He has used the Newtonian method of abstracting certain conceptions from the observations, and describing the observations themselves mathematically in terms of those conceptions. By the method of pure abstraction, therefore, he has correlated a much larger body of our common experience than was possible by the Newtonian mechanics.

"The net result of Einstein's great theory, then, is that we can now regard the whole mechanical and electro-magnetic phenomena of Nature as a manifestation of the characteristics of one abstract medium—space-time, or ether, or whatever else we care to call it. The Newtonian conceptions of space, time, mass, gravitation, momentum, as well as energy and electric and magnetic forces, all take their places as specified peculiarities of this medium. To Newton, space and time were the stage on which the drama of forces and motions were played. To Einstein, the drama is merged into the stage; the play is the scenery. Abstraction can hardly go further."

(3) From Chapter V, *The Extremity of Hypothesis—The Quantum Theory*:

"The hypothetical atoms and their parts, which were at first instinctively subjected to the abstractions derived from the study of observed bodies, were liberated by Bohr and made recognizable as concepts capable of assuming any form and willing to serve under the sway of any principles which might be found necessary to enable them to correlate observations. Accordingly they have been released from the duty of presenting a spatio-temporal aspect,

and in fundamental researches no attempt is made to conceive them in a pictorial form.

"The significant step was the liberation of the atomic hypothesis from the abstractions of phenomena. We must now regard the whole atomic scheme as purely conceptual, and take care that we are not again enslaved by the idea that its elements are potentially observable. The significant thing is that we are free to make the atom whatever we like for the purpose of correlating observations. If we can make it in the image of a machine, well and good; if not, well and good also. The form the atom assumes is a matter of detail; the liberty to conceive of it as we please is what matters.

"Relativity is an abstraction, and the quantum theory is an hypothesis. The apparent absurdity of relativity is entirely a matter of limited experience, and that of the quantum theory is entirely a matter of limited thought. Relativity teaches us that if we were to travel about the universe at high speed we would discover, on returning to the Earth, that a longer time had elapsed than our perfectly accurate clocks would indicate.

"But the fantastic character of the quantum theory is quite different. No possible extension of experience can make us familiar with an electron which does not occupy time and space, for the electron is not something imaginable, but a pure thought-structure. It is therefore useless, and even positively harmful, to try to picture it. A more vivid imagination would help us to resolve the paradoxes of relativity, but it would simply hinder us in trying to resolve those of the quantum theory. Relativity teaches us about phenomena because the notions it deals with are abstracted from our experience of phenomena; it surprises us because it reveals possibilities of experience which we never contemplated. The quantum theory surprises us because it reveals *impossibilities* of experience which we never contemplated; we thought we were justified in extending to atoms the abstractions discussed in relativity, and we find that we were not. The combined effect of the two theories therefore, is to give us truer notions of the limitations of experience. It still remains for us to explore the possibilities of thought."

These extracts fail to do justice to the book as a whole. The book should be read right through.

CHAPTER LI

6. Professor W. de Sitter

Relativity is not an Hypothesis: Einstein's Work merely Supplements Newton's

The University of Leiden in Holland has been world famous for many centuries, and one of the most distinguished of its late professional staff was W. de Sitter, who held the chair of Astronomy and was Director of the Observatory. In November, 1931, he delivered the Lowell lectures at Boston, U.S.A., the subject-matter of which was the development of our insight into the structure of the universe. The lectures are published in his book, *Kosmos.* We quote from the Chapter on *Relativity and Modern Theories of the Universe.* De Sitter's method of showing that Relativity is *not* an hypothesis but, like Newton's law of gravitation, merely a generalization, though of a wider sweep than Newton's, is particularly illuminating. (Although de Sitter's own words are preserved, the chapter is much condensed, and readers should refer to the original book which is certainly worth pondering over seriously.)

" The theory of relativity may be considered as the logical completion of Newton's theory of gravitation, the direct continuation of the line of thought which dominates the development of the science of mechanics, from Archimedes through Galileo to Newton. Newton's theory had celebrated its greatest triumphs in the eighteenth and nineteenth centuries; one after another all the irregularities in the motions of the planets and the moon had been explained by the mutual gravitational action of these bodies.

" Gradually Newton's law of gravitation had become a model on which physical laws were framed, and all physical phenomena were reduced to laws which were formulated as attractions or repulsions inversely proportional to some power of the distance. Gradually, however, during the second half of the nineteenth century, the uncomfortable feeling of dislike of the action at a distance, which had been so strong in Huygens and other contemporaries of Newton, but had subsided during the eighteenth century, began to emerge again, and gained strength rapidly.

"This was favoured by the purely mathematical transformation, replacing Newton's finite equations by the differential equations, the potential becoming the primary concept, instead of the force, which is only the gradient of the potential. In electro-magnetism also the law of the inverse square had been supreme, but, as a consequence of the work of Faraday and Maxwell, it was superseded by the field. And the same change took place in the theory of gravitation. By and by the material particles, electrically charged bodies, and magnets—which are the things that we actually observe—come to be looked upon only as "singularities" in the field. So far this transformation from the force to the potential, from the action at a distance to the field, is only a purely mathematical operation. Whether we talk of a 'particle of matter' or of a 'singularity in the gravitational field' is only a question of a name. But this giving of names is not so innocent as it looks. It has opened the gate for the entrance of hypotheses. Very soon the field is materialized, and is called æther. From the mathematical point of view, of course, 'æther' is still just another word for 'field', or, perhaps better, for 'space'—the absolute space of Newton—in which there may or may not be a field. From the point of view of physical theory, however, the 'æther of space', as it used to be called, is not simply space, it is something substantial, it is the carrier of the field, and mechanical models are devised to explain how it does the carrying. These mechanical models have, of course, been given up long ago: they were too crude. But hypotheses have kept cropping up on all sides: electrons, atomic nuclei, protons, wave-packets, &c. Fifteen years ago, although an atom was no longer, as the name implies, just a piece of matter that could not be cut into smaller pieces, atoms, electrons, and protons were still thought of as mechanical structures; models of the atom were imagined, having the mechanical properties of ordinary matter. It is only comparatively recently that we have come to see that there is nothing paradoxical in the fact that an atom or an electron, which are not matter, may have properties different from those of matter, and must be allowed to do things that a material particle could not do.

"However, whilst in all other domains of physics hypotheses have been found successful in accounting for the observed facts, and replacing the formal laws, the case of gravitation stands apart. In the course of history a great number of hypotheses have been

proposed in order to 'explain' gravitation, but not one of these has ever had the least chance, they have all been failures. Why is that? How does it come about that we have been able to find satisfactory hypotheses to explain electricity and magnetism, light and heat, in short all other physical phenomena, but have been unsuccessful in the case of gravitation? The explanation must be sought in the peculiar position that gravitation occupies amongst the laws of nature. In the case of other physical phenomena there is something to get hold of, there are circumstances on which the action depends. Gravitation is entirely independent of everything that influences other natural phenomena. It is not subject to absorption or refraction, no velocity of propagation has been observed. You can do whatever you please with a body, you can electrify or magnetise it, you can heat it, melt or evaporate it, decompose it chemically, its behaviour with respect to gravitation is not affected. Gravitation acts on all bodies in the same way, everywhere and always we find it in the same rigorous and simple form, which frustrates all our attempts to penetrate into its internal mechanism. Gravitation is, in its generality and rigour, entirely similar to inertia, which has never been considered to require a particular hypothesis for its explanation, as any ordinary special physical law or phenomenon. Inertia has from the beginning been admitted as one of the fundamental facts of nature, which have to be accepted without explanation, like the axioms of geometry.

"But gravitation is not only similar to inertia in its generality, it is also measured by the same number, called the mass. The inertia mass is what Newton calls the 'quantity of matter': it is a measure for the resistance offered by a body to a force trying to alter its state of motion. It might be called the 'passive' mass. The gravitational mass, on the other hand, is a measure of the force exerted by the body in attracting other bodies. We might call it the 'active' mass. The equality of active and passive, or gravitational and inertial, mass was in Newton's system a most remarkable accidental coincidence, something like a miracle. Newton himself decidedly felt it as such, and made experiments to verify it, by swinging a pendulum with a hollow bob which could be filled with different materials. The force acting on the pendulum is proportional to its gravitational mass, the inertia to its inertial mass: the period of its swing thus depends on the ratio between these two masses. The fact that the period is always the same

therefore proves that the gravitational and inertial masses are equal.

"In Einstein's general theory of relativity the identity of these two coefficients, the gravitational and the inertial mass, is no longer a miracle, but a necessity, because gravitation and inertia are identical.

"The physical world has three space dimensions and one time dimension; the position of a material particle at a certain time t is defined by three space coördinates, x, y, z. In Newton's system of mechanics this is unhesitatingly accepted as a property of the outside world: there is an absolute space and an absolute time. In Einstein's theory time and space are interwoven, and the way in which they are interwoven depends on the observer. Instead of three plus one we have four dimensions.

"The sequence of different positions of the same particle at different times forms a one-dimensional continuum in the four-dimensional space-time, which is called the *world-line* of the particle. All that physical experiments or observations can teach us refers to intersections of world-lines of different material particles, light-pulsations, &c., and how the course of the world-line is between these points of intersection is entirely irrelevant and outside the domain of physics. The system of intersecting world-lines can thus be twisted about at will, so long as no points of intersection are destroyed or created, and their order is not changed. It follows that the equations expressing the physical laws must be invariant for arbitrary transformations.

"This is the mathematical formulation of the theory of relativity. The metric properties of the four-dimensional continuum are described by a certain number (ten, in fact) of quantities, and commonly called 'potentials'. The physical status of matter and energy, on the other hand, is described by ten other quantities, the set of which is called the 'material tensor'. The fundamental fact of mechanics is the law of inertia, which can be expressed in its most simple form by saying that it requires the fundamental laws of nature to be differential equations of the second order. Thus the problem was to find a differential equation of the second order giving a relation between the metric tensor and the material tensor. This is a purely mathematical problem, which can be solved without any reference to the physical meaning of the symbols. The simplest possible equations of that kind that can be found were adopted

by Einstein as the fundamental equations of his theory. They define the space-time continuum, or the 'field'. When we come to solve the field-equations and substitute the solutions in the equations of motion, we find that in the first approximation, i.e. for small material velocities (small as compared with the velocity of light), these equations of motion are the same as those resulting from Newton's theory of gravitation. The distinction between gravitation and inertia has disappeared; the gravitational action between two bodies follows from the same equations, and *is* the same thing, as the inertia of one body.

"In the first approximation, as has been said just now, the new theory gives the same results as Newton's theory of gravitation. The enormous wealth of experimental verification of Newton's law, which has been accumulated during about two and a half centuries, is therefore at the same time an equally strong verification of the new theory. In the second approximation there are small differences, which have been confirmed by observations, so far as they are large enough for such a confirmation to be possible. Thus especially the anomalous motion of the perihelion of Mercury, which had baffled all attempts at explanation for over half a century, is now entirely accounted for. Further the theory of relativity has predicted some new phenomena, such as the deflection of rays of light that pass near the sun, which has actually been observed on several occasions during eclipses; and the redshift of spectral lines originating in a strong gravitational field, which is also confirmed by observations, e.g. in the spectrum of the sun, and also in the spectrum of the companion of Sirius.

"Two points should be specially emphasised in connection with the general theory of relativity.

"1. First that it is a purely *physical* theory, invented to explain empirical physical facts, especially the identity of gravitational and inertial mass, and to coördinate and harmonise different chapters of physical theory, and simplify the enunciation of the fundamental laws. There is nothing metaphysical about its origin. It has, of course, largely attracted the attention of philosophers, and has, on the whole, had a very wholesome influence on metaphysical theories. But that is not what it set out to do, that is only a by-product.

"2. Second that it is a pure generalisation, or abstraction, like Newton's system of mechanics and law of gravitation. It contains *no hypothesis*, as contrasted with other modern physical theories,

electron theory, quantum theory, &c., which are full of hypotheses. It is, as has already been said, to be considered as the logical sequence and completion of Newton's Principia."

CHAPTER LII

7. Max Born

Nuclear Physics

Max Born, the distinguished mathematical physicist, is now Stokes Lecturer in Mathematics at Cambridge. In his book *The Restless Universe,* from which we quote, he tells us how the whole structure of a new mechanics, known as *quantum mechanics,* was gradually built up by better and better interpretation of facts about spectra. A " decisive idea " which had been put forward by Heisenberg in 1925 was seized upon by himself and Jordan and they worked out the appropriate mathematics, the so-called *matrix mechanics.* In his earlier days Born had gone " just for fun " to a lecture on an abstruse subject, and had speedily forgotten all about it save for the word " matrix " and a few simple theorems about matrices. Born, playing about with Heisenberg's formula, revived his memory of matrices, associated the two things, and quantum mechanics was born.

We quote from the chapter on *Nuclear Physics.* The book contains a great wealth of most suggestive and useful illustrations. Plate VIII " The Synthesis of Matter " is, in particular, worth very careful study.

" *The Deuteron.*

" Hydrogen and oxygen play a special part in practical physics. Their compound, water, is used as a standard substance in many measurements. For example, when the metric system of units was set up, the unit of mass (the gramme) was originally defined as the mass of a cubic centimetre of water at a definite temperature. Again, the centigrade scale of temperature is associated with the boiling-point and the freezing-point of water. Similarly in many other

cases. Oxygen serves as the standard of atomic weight, and the hydrogen nucleus, the proton, is the unit of nuclear structure. All this is based on the idea that pure hydrogen, pure oxygen, and pure water are well-defined substances.

"The first of the discoveries which we have to consider plays havoc with this assumption: for both hydrogen and oxygen are found to be mixtures of isotopes. Although in both cases the quantity of the one isotope is enormously large compared with that of the other, yet in the case of hydrogen, at least, we are faced with the serious fact that the rarer isotope is just twice as heavy as the ordinary one. In all other cases the difference between the weights of the isotopes is fairly trifling compared with their own weights. For this reason they are difficult to separate and play no great part in the everyday life of the physicist or chemist. *Heavy hydrogen*, however, is really quite a different substance from ordinary hydrogen, and hence has been given a special name. The nucleus with charge 1 and mass 2 is called a *deuteron* (Greek *proton*, the first; *deuteron*, the second), and the corresponding element (heavy hydrogen) is often called *deuterium*, its symbol being D.

"Molecular hydrogen really consists of three gases, namely, ordinary H_2, HD_1, and D_2; the latter is of course only present in very minute amount. Water also consists of three different sorts of molecules, H_2O, HDO, and D_2O. In electrolysis the lighter H_2 is liberated five or six times as rapidly as the other kinds of hydrogen; hence the heavy isotope accumulates in the water left behind. By electrolysing the residue over and over again, almost pure *heavy water* (D_2O) is thus obtained. To-day heavy water can actually be bought—at least if one has plenty of money, for the process by which it is manufactured is expensive.

"The molecular weight of heavy water is $2 \times 2 + 16 = 20$, as compared with $2 \times 1 + 16 = 18$ for ordinary water; that is, the difference is as much as 10 per cent! The exact mass of the D nucleus is 2·0136; deducting this from the mass of two protons, $2 \times 1{\cdot}0078 = 2{\cdot}0156$, we obtain the mass-defect or energy of formation of the deuteron, namely, 0·0020. This is very much smaller than the energy of formation of the helium nucleus, which is 0·030. The properties of "heavy water" (D_2O) differ very considerably from those of ordinary water (H_2O); its freezing-point is 3·8° and its boiling-point 1·4° higher, and its density actually 11 per cent greater!"

" *The Neutron.*

" The idea that the atoms of electricity, the electron and the proton, are the ultimate units out of which matter is built up was a simple and beautiful one. But, alas, it is wrong. There are other particles as well which have an equal right to the title of ultimate atoms.

" In the first place, it was found that *neutrons* do actually exist. Their discovery is closely bound up with another discovery, namely, that nuclei can be excited and made to emit light, just as atoms can. This had been suspected for a long time. The γ-rays, of the same nature as light, which are emitted by radioactive substances, can be explained in the following way. When a nucleus explodes, the nuclear residue does not remain in the ground-state, but in an excited state, subsequently jumping back to the ground-state and emitting a proton. Thus the γ-rays indicate the existence of energy-levels in such nuclei as form the end-product of a nuclear explosion. Do these energy-levels not exist in ordinary nuclei also?

" Bothe and Becker did actually succeed in causing light nuclei, lithium and beryllium, to emit γ-rays, by bombarding them with α-rays.

" Chadwick recognized that it was *neutrons* that are liberated from beryllium on bombardment with α-rays. For the point where the proton becomes visible in the form of a cloud-track is not connected with the beryllium by another cloud-track; the new radiation has no effect on the external electrons of the atoms, and therefore cannot consist of anything but uncharged particles. These must have a mass about equal to that of the proton, and if they collide centrally with a proton, they set it in motion. It is even possible to determine the mass of the neutron very accurately, by comparing the results of its collisions with various nuclei, such as those of hydrogen and nitrogen. The result is that the neutron is found to have the same mass as the proton.

" These neutrons behave quite differently from all kinds of rays previously known, whether of light or of charged particles. When the latter pass through matter, the process of retardation and finally of absorption is chiefly a matter of their energy being given up to the external electrons of the substance. As the number of external electrons is approximately proportional to the nuclear mass, the intensities of absorption of different substances are approximately

proportional to their masses. Thus a layer of lead has a much more powerful retarding effect than an equally heavy layer of aluminium or of paraffin-wax. In the case of neutrons it is quite different. Neutrons pay no attention to the external electrons, but are retarded only by direct collisions with nuclei. As the latter are almost all about the same size, it is a question of the number of nuclei per cubic centimetre. Here, however, the lighter substance has the advantage. For 1 gramme of hydrogen contains 16 times as many nuclei as 1 gramme of oxygen, i.e. has 16 times as great a retarding effect on neutrons. Neutrons penetrate through thick layers of lead, which are a sure protection against all other kinds of rays, and are held up by thin layers of light substances, which are no obstacle at all to α-rays. Hydrogen has a peculiar effect, in that it does not stop the neutrons completely, but merely retards them; quite slow neutrons can be produced with the help of a layer of paraffin-wax or water. This is obviously due to the fact that the neutrons have about the same mass as the hydrogen nuclei and hence in colliding with the latter give up about half their energy.

" What is a neutron like, then? It may be imagined as being a very close combination of an electron and a proton, in which the binding is much closer and stronger than the binding between the electron and the proton in the hydrogen atom. Why two such types of combination should exist, one firm and one loose, is quite unknown.—Yet another new and important discovery followed, which opened up new possibilities of explanation."

" *The Positron: Cosmic Rays.*

" None of the theories of electricity hitherto put forward gives the least clue to any explanation of the fact that positive electricity and negative electricity do not occur in exactly the same way, but in the form of the proton and the electron, with their widely differing masses. It had long been conjectured that positive electrons (of small mass) and negative protons (of large mass) could also exist; but it was only the quantum mechanics in its most refined form, due to Dirac, that led to the definite opinion that this must be so. The *positive electrons* or *positrons* were actually discovered from observations of a wonderful phenomenon known as the *cosmic rays*. These in themselves are of very great interest, and we shall accordingly give a brief account of them here.

"Even in empty space there is no rest. Everywhere light-waves coming from the luminous stars are in continual oscillation. Here and there an atom is found wandering about by itself; their density in interstellar space is estimated at about 1 atom per cubic centimetre. Further, the sun is continually shooting out very fast electrons; these give rise to the aurora ('northern lights'). For we know that an electron is deviated by a magnetic field, in a corkscrew-like path, the coils of which become closer, the stronger the field and the slower the electron. Now it is well known that the earth is a magnet. The electrons shot out by the sun come into the earth's magnetic field and are deflected into spiral paths winding round the magnetic poles of the earth. Størmer has worked out these paths and has shown that no electrons can reach the equatorial regions, but that they must accumulate in high northern and southern latitudes. The phenomenon can even be imitated experimentally by letting cathode rays fall on a small magnetized iron sphere.

"These electrons are also responsible for the existence of a layer of ionized gases very high up in the atmosphere, the so-called Kennelly-Heaviside layer, which, strange to say, is of great importance for us. For it is electrically conducting and acts like a mirror for electric waves, just as a metal mirror does for light. This is why our radio transmitters have such a wide range, in spite of the curvature of the earth; the waves cannot get out into space, but are thrown back, once, twice, or many times, and thus reach the surface of the earth at a great distance, so that we can hear music from America.

"The electrons from the sun, however, do not actually reach the surface of the earth; but there are other missiles flying through space with colossal energies, some of which do reach us. It is about twenty-five years since this barrage was first noticed on the earth. The ionization chambers used to detect radiations in the laboratory never show absolutely *no* current; counting apparatus, too, always gives a few deflections. This is partly due to the fact that everywhere in the earth there are traces of radioactive substances, which occasionally send a particle through the apparatus. But even when the apparatus is shielded as far as possible from terrestrial effects by thick sheets of lead, there always remains some radiation which cannot be got rid of.

"Hess was the first to take an ionization chamber up with him

in a balloon; he found that the radiation increased as he went up. Later these experiments were extended to great heights by means of aeroplanes and balloons with or without observers, as in Piccard's celebrated stratosphere flight. The greatest heights reached with balloons carrying self-registering apparatus are about 30 kilometres. These observations clearly indicate that the radiation falls on the earth from outside. It cannot originate in the highest layers of the earth's atmosphere, say, as a result of the electrical tensions which are discharged in the lower layers of the atmosphere by thunderstorms. For it was proved that the radiation decreases slightly towards the equator; the natural explanation of this is that the radiation consists of charged particles, which come from outer space into the magnetic field of the earth and are deviated by it, just like the electrons which cause the aurora, but to a much smaller extent, owing to their greater velocity. The radiation does not come from the sun, or from the Milky Way, or from any other special direction. It seems to fill all space. Its energy must be immensely great; for it can be detected at the bottom of deep lakes 500 metres below the surface of the water.

"At last experimenters succeeded in making the particles of which the radiation consists visible in the Wilson chamber. The whole chamber was put between the poles of a strong magnet, and curved tracks were then seen. The energy can be calculated from the curvature, and the particles are found to have energies equal to those of electrons which have been subjected to an electrical tension of several hundred or even thousand million volts.

"But these rays, which are observed here on the surface of the earth, are certainly not the original cosmic rays alone, but a mixture of these with secondary rays produced by the cosmic rays as they pass through the matter in the atmosphere or apparatus.

"It was these rays originating mysteriously somewhere in space that drew attention to the existence of positive electrons. Anderson was the first to notice that often the same plate will exhibit tracks of opposite curvatures, which appear to come from the same point of the wall of the chamber. He was also the first to express the view that they were due to positive electrons. They could not be proton-tracks, for they looked exactly like those of ordinary electrons. The possibility that the tracks curving the wrong way were due to ordinary negative electrons moving backwards seemed improbable, in view of the common starting-point of the tracks; whole showers

of particles were found, which must obviously arise from a sort of explosion in the nuclei of the atoms of metal in the apparatus when struck by a cosmic particle. At last it was proved directly that the suggestion that the paths are described backwards will not do. A lead plate was placed in the chamber, and particles were occasionally observed to pass through the plate. Where the path is more strongly curved, the particle is slower; the lead plate can, of course, only *retard* the particles, so the direction of their motion is definitely indicated. The results led perforce to the conclusion that positive electrons occur in the cosmic radiation.

"Soon it was also found possible to produce positive electrons in other ways. When light elements are bombarded with γ-rays, electron-pairs are observed to appear in the Wilson chamber, a positive electron and a negative electron shooting out from the same place.

"These and similar observations raise a host of questions: why do the positrons occur so rarely in the universe? Do they lie hid in the nuclei? Are they liberated from there by light? Why is a positron always accompanied by a negative electron?

"The answers to the last two questions were given by the theory of Dirac even before the experiments had led to them being asked; and the results have now been confirmed by new direct experiments. A bold assertion is made, and yet one that is consistent with the line which physics has followed from the beginning: matter does not persist from eternity to eternity, but can be created or destroyed. A positive electron and a negative electron may annihilate one another, their energy flying off in the form of light; but they can also be born, with the annihilation of light-energy.

"Once the equivalence of mass and energy had been recognized, the possibility that material particles, electrons in particular, can be created or destroyed was often thought of. But now the phenomenon is made visible to our eyes. For in the Wilson chamber we actually see the birth of an electron-pair. The reverse process, the collision and vanishing of a positive electron and a negative electron, has been demonstrated with equal certainty.

"The state of affairs is therefore as follows: each electron seeks for a partner of the opposite kind and rushes to unite with it. In this wild wedlock the parents disappear and a pair of twin photons are born. But not all electrons find a partner. In our part of the universe there is a superfluity of the negative kind. Why? We have